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in our range of flow parameters ($2.7 < M < 2.9$, $3\times10^4 < Re_D < 4\times10^5$, $0.04 < \delta^*/D < 0.10$), is less than that found in usual wind tunnel applications. With relatively thick boundary layers and a strong dependence of the pressure recovery on shock wave - boundary layer interactions, it is difficult to find an optimum geometric configuration to cover a range of flow parameters. Another finding is, that a reduction of the adjustable second throat area beyond the minimum starting value is possible after the flow is established. Yet in contrast to conventional wind tunnel results, no greatly improved pressure recovery is observed in doing so. This means that in our case of narrow ducts, a fixed geometry diffuser performs practically as well as the more complicated adjustable one. The results described here for a simple duct could be applicable to the multiple nozzles of some type of gas-dynamic lasers operating at about the same flow conditions.

ABSTRACT

Following an investigation of a simple, rectangular constant area duct supersonic diffuser, three types of variable area diffusers have been tested. Again these diffusers consisted essentially of a duct, but with two opposing pivoting elements to form a second throat smaller than the nozzle exit area. As expected, the performance of a refined diffuser can be better than that of a simple duct. However, the gain in our range of flow parameters ($2.7 < M < 2.9$, $3\times10^4 < Re_D < 4\times10^5$, $0.04 < \delta^*/D < 0.10$), is less than that found in usual wind tunnel applications. With relatively thick boundary layers and a strong dependence of the pressure recovery on shock wave - boundary layer interactions, it is difficult to find an optimum geometric configuration to cover a range of flow parameters. Another finding is, that a reduction of the adjustable second throat area beyond the minimum starting value is possible after the flow is established. Yet in contrast to conventional wind tunnel results, no greatly improved pressure recovery is observed in doing so. This means that in our case of narrow ducts, a fixed geometry diffuser performs practically as well as the more complicated adjustable one. The results described here for a simple duct could

be applicable to the multiple nozzles of some types of gasdynamic lasers operating at about the same flow conditions.

OUTLINE

SYMBOLS*

A	=	Area
D	=	Hydraulic diameter(D = 4 times area divided by circumference). Nozzle exit area (1.91×0.95) cm^2, D = 1.27 cm = constant.
L	=	Diffuser length.
M	=	Mach number.
p	=	Static pressure.
p_t	=	Pitot pressure.
Δp	=	Diffuser pressure recovery ($\Delta p = p_{max} - p_{initial}$)*
Re_D	=	Reynolds number based on hydraulic diameter and test section free stream parameters. ($Re_D = (v\rho D)/\mu$).
T	=	Temprature.
v	=	Flow speed.
x	=	Axial distance,at nozzle exit $x = 0$.
x**	=	Position of the second throat.
Δx	=	Length of pressure recovery zone (from start of pressure rise to maximum pressure)*
δ	=	Boundary layer thickness.
δ*	=	Boundary layer displacement thickness.
ρ	=	Density.
μ	=	Dynamic viscosity.

Subscripts: 0 = Reservoir, nozzle supply.
1 = Nozzle end.
2 = Diffuser end.

* See Figure 3.

1. INTRODUCTION AND EXPERIMENTAL ARRANGEMENT.

With new application of supersonic diffusers in novel devices, among them gasdynamics lasers (Russell[1], Clawson[2], Nuttbrock[3], Zerr[4], Fishburne et al.[5]) and rotating machinery (Cnossen and O'Brien[6], Waltrup and Billig[7]), new interest in the performance of supersonic diffusers has arisen in the past few years. With markedly different flow parameters (Reynolds number, Re_D, and boundary layer parameter, e.g. δ^*/D) than in conventional wind tunnel applications, a lack of systematic knowledge became apparent. This fact stimulated new research in the field. The interest focuses on the possible pressure recovery in narrow diffusers or even rows of diffusers, as found e.g. in gasdynamic lasers. With narrow flow channels and many parallel diffusers, the simplicity of the design becomes a key factor. Therefore the simplest supersonic diffuser, the straight duct has gained renewed attention. Since the last survey of diffuser performance dated back to 1953, (Lukasiewicz[8]), our program under the subject contract started with a literature survey of the present knowledge by Johnson and Wu[9]. Next a systematic experimental investigation of the influence of the Reynolds number, Re_D, Mach number, M, and boundary layer thickness parameter, δ^*/D, on the performance of the constant area duct was undertaken (Merkli[10]). The present paper extends this work to some simple adjustable geometry diffusers to determine if improvements in pressure recovery can readily be achieved.

The experiments reported here were conducted in the same continuous wind tunnel (Stein[11]) previously used for the constant area duct investigation (Fig. 1). Oilfree, compressed, dry air at supply pressures of 200 Torr < p_o < 3050 Torr and at a supply temperature of $T_o \approx 300$ K was used. The uniform flow supersonic nozzle as designed with the method of characteristics for isentropic M = 3 flow was the same as that of the previous work†. The various diffusers used were installed in a constant area duct with length L/D = 15 beyond the nozzle exit. Two motorized opposing slides were used to form the second throat for the three arrangements shown in Fig. 2. These gates could be located at x**/D = 3; 6; 9 and 12 by inserting constant area sections of various lengths following the nozzle and prior to the contraction leading to the second throat. Static pressure measurements were made at pressure taps (at 1 D intervals, inside diameter ≈ 0.1 cm)

† Throat area, $A^* = (0.45 \times 0.95)\ cm^2$, exit area, $A_x = (1.91 \times 0.95)\ cm^2$, hydraulic diameter, D = 1.27 cm, effective Mach number, $M \approx 2.9$.

along the centerline of the flat nozzle extending to the wider diffuser sidewall. Using two scanning valves, pressure at 24 locations could be measured in our experiment. The pitot pressure was measured in the center of the diffuser exit plane and some pitot surveys across the exit plane were performed. Using Statham strain gauge pressure transducers and Heath-Schlumberger strip-chart recorders, measurements were made to an accuracy of roughly ±1% of the required full recorder range.

The best pressure recovery results are obtained for the recovery zone (see Fig. 3) starting immediately at the nozzle exit. Taken from earlier work (Merkli[10]), Fig. 4 gives the flow parameters prevailing at this location.

2. THE GATE DIFFUSER.

Since the flow in the recovery zone (Fig. 3) is in general separated from the walls due to the high adverse pressure gradient, it was tried to decrease the second throat area beyond the one occurring naturally in the separated region of the straight duct. Such a decrease in area ought to increase the pressure recovery. Thus a gate diffuser as seen in Fig. 2A was constructed for the purpose.† The experiments showed, however, that

† This opposing pair of motor-driven slides simultaneously serves as the pivoting mechanism for the other configurations of Fig. 2.

independent of the second throat x-position, no improvement over the corresponding straight duct pressure recovery could be achieved. It appears that as long as the slides remain submerged in the separation zone, they have little or no effect on the pressure recovery. However, as soon as they protrude into the free stream, the flow becomes choked as expected and the subsequent breakdown of the flow propagates upstream into the nozzle. As seen from the pressure distributions in Fig. 5, the slides give rise to a waviness superimposed on the pressure increase.† Yet the overall recovery length is the same as for the simple straight duct. Fig. 6 shows that the location of the incipient pressure recovery moves upstream with a decreasing diffuser throat area at a fixed position x^{**} of the second throat. The same effect is observed if the back pressure is increased for a fixed second throat height, h^{**}/h, since as in the constant area duct the pressure recovery is higher if the pressure increase originates closer to the nozzle exit.††

† This pressure variation appears here and in later configurations in steady flow. The pressure distribution is undoubtedly smoothed by the boundary layer effects on the sidewall.

†† Since the channel width is constant, the ratio h^{**}/h is the same as the area ratio A^{**}/A.

In summary, as might be expected, the experiment indicates that the use of such a simple adjustable diffuser provides no advantage over the straight duct.

3. THE FLEXIBLE WALL DIFFUSER.

It is well known (e.g. Hermann[12]) that diffuser losses may be reduced by gradually deflecting the supersonic flow, and thus causing several weak oblique shock waves to reduce the flow Mach number. We recall that the overall shock loss through one or more oblique shocks followed by a normal shock at a lower Mach number is less than that of a normal shock at the same initial Mach number. One diffuser producing such an oblique shock system is shown in Fig. 2B. Here flexible sheets are mounted on the movable slides. With fully retracted supports, the constant area duct is reproduced, with $h^{**}/h = 1$.

Of primary interest are the maximum possible static and pitot pressure recoveries depending on second throat height, h^{**}/h, and streamwise location x^{**}/L of the diffuser throat. Figs. 7 to 9 show results for three supply pressure $p_o = 400$, 765 and 2285 Torr, corresponding to $Re_D = 5.17\times10^4$, 9.88×10^4 and 2.95×10^5 respectively. We note that the optimum pressure recovery, though slightly higher for the lower Reynolds numbers, is much the same in all cases. The performance of the straight duct though is markedly poorer for the lower Reynolds numbers than for the higher ones, see Fig. 7-9 for $h^{**}/h = 1$. This means that, compared with the straight duct diffuser, the flexible wall diffuser yields relatively better pressure recoveries at the low Reynolds numbers (i.e. + 40% at $Re_D = 5.17 \times 10^4$ versus + 17% at $Re_D = 2.95 \times 10^5$). As expected, the same static and pitot pressure recoveries are found for $h^{**}/h = 1$ as in the earlier experiments with the straight duct as seen in Fig. 10. Compared with inviscid nozzle flow followed by a normal shock at the nozzle exit Mach number, the best results for the straight duct yield 0.77 times the normal shock static pressure recovery. With the flexible wall diffuser this performance could be improved to 0.94. A more realistic comparison would, of course, in addition have to take the frictional pressure losses in the nozzle into account which at best can only be estimated.

The limiting minimum second throat area ratios for starting the wind tunnel and for flow breakdown (which are the same as the ratios h^{**}/h, since the channel width is constant) are indicated in Figs. 7, 8, 9 and 11. Both ratios are found to increase for throat positions, x^{**}/D, further downstream. While the starting limits exhibit little scatter for different values of Re_D, some scatter is observed for the break down limit. It is also seen that the starting area ratios of h^{**}/h are close to the values estimated by Hermann[12]. However, the second throat break down area ratios are always greater than Hermann's values. Since his work applies to larger wind tunnels this is not surprising.†

Contrary to expectations practically no increase in maximum static pressure recovery is realized by closing the second throat beyond the starting limit, once the flow is established, as seen from Figs. 7 to 9. While the reason for this behavior is presently not fully known, it may coincidentally well be related to the particular configuration studied.

The results on pressure recovery shown in Figs. 7 to 9 may give the impression that for diffuser throat locations $x^{**}/D > 9$, the adjustable diffuser achieves no improvement with respect to the straight duct, which is reproduced for $h^{**}/h = 1$. It has to be kept in mind,

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† Hermann calculates the minimum starting area ratio as a function of M_1 considering the possibility of the second throat to swallow a normal shock standing ahead of it during the starting sequence (swallowing function). The minimum running area ratio is based on experiments with various wind tunnels.

however, that the best performance of the straight duct occurs if the recovery zone starts immediately at the nozzle end. Yet by increasing the values of x^{**}/D for the flexible wall diffuser, the recovery zone is shifted downstream to less favorable recovery conditions, characterized by thicker boundary layers. Comparing static pressure recovery uniformly, i.e. for identical locations of the start of the recovery zone leads to the results shown in Fig. 12. It is seen that the flexible wall diffuser always out-performs the straight duct. For example a pressure recovery starting at $x_r/D \approx 9$ for the flexible wall diffuser still leads to the same recovery as one starting immediately at the nozzle end for the straight duct. Of course, for second throat positions close to the duct end, the remaining section is too short to reach full pressure recovery. In turn imposing a high back pressure can lead to a pressure recovery zone in the straight duct well ahead of the second throat, thus rendering the movable diffuser superfluous. This effect explains the apparent independence of the static pressure recovery on the second throat opening, h^{**}/h, as noted e.g. for $x^{**}/D = 12$ in Figs. 7 to 9.

To test if the diffuser length beyond the second throat is too short to achieve full pressure recovery, some experiments with twice the usual duct length, (i.e. $L/D = 30$) have been performed. Fig. 13 shows that indeed for $x^{**}/D > 9$ some additional pressure recovery does take place for $x/D > 15$. Doubling the duct length in turn also results in added frictional losses, which exceed the favorable effects in this situation. Maximum static and pitot pressure recovery measured with this arrangement are given in Figs. 14 to 16. As expected the additional duct length did not influence the minimum starting and break down area ratios of the second throat since none of the flow parameters at the start of the pressure recovery zone are altered by adding to the original duct length.

With the pressure recovery accomplished and therefore with subsonic flow at the diffuser exit, the static pressure is constant across the duct cross section. Therefore a single measurement of static pressure on the wall suffices to determine diffuser performance. This situation does not prevail for the pitot pressure which, due to the velocity profile, usually varies across the flow cross section as we shall show. For this reason a comparison of diffuser performance based on pitot pressure measurements at the diffuser exit as often found in the literature ought to be avoided, since it is based on an arbitrarily chosen mean value. The choice of the averaging procedure of such pressure values may be the reason for some remarkably high values of pressure recovery as reported in the literature (e.g. Cnossen and O'Brien[6], citing pressure recoveries up to more than two times normal shock recovery at the test section Mach number in fully viscous flow). Figs. 7 to 9 and 14 to 16 show the pitot pressure measured in the center of the diffuser exit plane for maximum static pressure recovery for the cases L/D = 15 and L/D = 30 respectively at various supply pressures. It is striking that for the L/D = 15 diffuser and second throat positions close to the diffuser exit, i.e. $x^{**}/D = 9$ or 12 in Figs. 7 to 9, the measured pitot pressure increases stepwise to high values with a reduction of the diffuser throat area ratio. Unfortunately this result does not indicate a high pressure recovery, since the pitot probe is thought to be located in a central, local supersonic flow region giving rise to the high pressure values. As seen in Figs. 14 to 16 an extension of the duct to allow for a return to low speed flow does not give such favorable results. In all other cases the pitot pressure varies smoothly with the second throat area. For the static pressure recovery, we noted that if the pressure recovery is poor for the straight duct ($h^{**}/h = 1$), the closing of the second throat results in a higher gain than if the pressure recovery is already better for the simple straight duct. This is true also for the pitot pressure. If the entire pressure recovery zone is located in the diffuser, the best pitot pressure recoveries in the center of the diffuser exit plane are about 0.95 times the ones computed for a normal shock at the nozzle exit Mach number.

Figures 17 and 18 illustrate the previously discussed difficulty to define a representative recovery pitot pressure. Fig. 17 gives results of pitot pressure surveys across the channel in the exit plane. For low back pressures, the pressure profile is indented in the center. This ceases to be the case for high back pressures. The pitot pressure tends to become uniform only when the recovery zone has moved into the nozzle and the undisturbed nozzle flow thus is broken down. In Fig. 18 the pitot pressure is plotted for different positions in the diffuser exit plane for changing back pressures. Regarding the curve of the center of the exit plane ($y/h = 0.5$), we find the lowest pitot pressures for the best diffuser performance, e.g. the highest back pressure that can be imposed without flow break down in the nozzle. Reducing the diffuser performance by decreasing the back pressure results at first in a peaking of the pitot pressure and then a leveling at high values.

Finally, we note the static pressure distributions along the flexible wall diffuser in Fig. 19. A gradual increase in static pressure is noted in front of the second throat. However, if the back pressure is too low, the gas expands again after the second throat, and the actual pressure recovery takes place further downstream. For optimum pressure recovery of the diffuser the expansion after the second throat vanishes as seen in Fig. 20. Although the pressure distributions in the flexible wall diffuser and the simple straight duct are somewhat different, the recovery length for maximum pressure recovery is remarkably alike in both cases. As mentioned earlier, for positions of the second throat that are far from the nozzle end, and for high back pressures, the pressure recovery can be forced to occur in the straight duct ahead of the second throat. This is illustrated by Figs. 21 and 22. We have then returned to the conditions of the constant area duct.

The addition of an efficient subsonic diffuser of a small divergence angle beyond the convergent flexible plate was not pursued since the overall pressure recovery obtained by adding a subsonic diffuser can be estimated. This gain in pressure recovery is unfortunately found to be small.

4. THE WEDGE DIFFUSER.

For the reasons previously stated the use of oblique shocks to reduce the flow speed renders the classical wedge type diffuser an attractive possibility for pressure recovery. In our experiment the wedge angles of the adjustable diffuser (Fig. 2C) were designed so that in the closed position of the slides to which the wedges are attached, two oblique shocks at an angle of 38° for a deflection angle of 20.3° computed for inviscid flow should decelerate the flow to $M = 1.02$ at the second throat. As recommended by other investigators (i.e. Neumann and Lustwerk[13], Hastings and Roberts[14]), the throat was extended into a nearly constant area channel section with a final sudden opening. If the diffuser operates properly subsonic speed is expected at the exit. Moreover in the fully open position the diffuser throat was designed to permit starting of the flow according to the previous experiments. Since high speed flows in narrow channels at the Reynolds number of our experiments exhibit appreciable frictional pressure losses, it is desirable to slow down the flow as close to the nozzle exit as possible without affecting the flow in the test section. Therefore, the second throat was moved further upstream with respect to the earlier experiments.

The flow could be started with the fully opened second throat ($h^{**}/h = 0.711$) located at $x^{**}/D = 1.2$, the closest possible position to the nozzle exit in our design. However, as seen from Fig. 23, even for the lowest back pressures, a pressure increase near the nozzle exit was noted. This disturbing effect was most likely caused by feedback from the diffuser. This result necessitated moving the throat to a position further downstream where $x^{**}/D = 4.2$. Once the flow had started in this configuration, the second throat could only be closed very little beyond the starting limit without causing the flow to break down. This effect was thought to result from the rather thick boundary layers $\delta/D \sim 0.17$ at the nozzle exit for $p_o = 400$ Torr, corresponding to $Re_D = 5.2\times10^4$, that is for the case of Fig. 24). Therefore boundary layer suction was applied through slots at the root of the wedges as seen in Fig. 2C. The suction equipment allowed the removal of some 40 to 50% of the mass in the boundary layer displacement thickness over the wedge entry, corresponding to roughly 4% of the total mass flow. As seen from Fig. 24 the upstream disturbance could be reduced but not fully eliminated by this means. An increased mass flow by suction would certainly further improve the situation. However, mass removal presents a problem at the low pressures prevailing. Clearly boundary layer blowing would be easier and should be tried. Here advantage could be taken by the higher outside pressure. Even with suction the second throat could not be closed anywhere near to the optimum design configuration. Therefore no high pressure recovery results were noted.

For low supply pressures, i.e. at low Reynolds numbers or relatively thick boundary layers at the nozzle exit, the performance shown in Fig. 25 was found. Surprisingly, the second throat area could be reduced most effectively at low Reynolds numbers. For the high supply pressures, that is for thinner boundary layers, the undisturbed nozzle flow could only be maintained with suction, even for the fully opened second throat with $h^{**}/h = 0.711$. In the intermediate supply pressure range there is a region where the second throat can be closed to a smaller area if the suction is shut off. Clearly, a complex flow pattern in the diffuser must be assumed to understand this unexpected behavior.

Fig. 26 shows the optimum static pressure recovery for the fully opened second throat, $h^{**}/h = 0.711$. Expecting the lowest supply pressures, where the Mach number rapidly falls below $M = 2.88$ due to boundary layer effects (Merkli[10]), the results are much the same for all pressures with and without suction. The pressure recovery values of the wedge type diffuser are equivalent to or slightly better than the results for the simple straight duct diffuser. Fig. 27 finally gives the variations of the maximum static pressure recovery with changing second throat area (or height). It is seen that the flow is always close to break down. As in the earlier experiments, the recovery lengths here are found to be about the same as the ones observed for the straight duct.

In summary the particular configuration of our wedge diffuser offers no advantages over the straight duct. This, of course, does not demonstrate that the wedge diffuser can not work well. Certainly, for one specific condition (Mach number, Reynolds number, boundary layer parameter) an optimum solution could be found, by computing shocks and shock wave - boundary layer interactions. The experience with the experiments described here, moreover, demonstrates what can happen if this diffuser is operated at off-design conditions. A better understanding of the detail of these flow phenomena would certainly result from photography. However, in summary it appears that unless a single design print is of interest, the wedge diffuser does not provide an attractive alternative to the straight duct.

5. CONCLUSIONS.

In conventional high Reynolds number wind tunnel applications of supersonic diffusers the shock losses dominate the frictional losses. An optimization of supersonic diffuser recovery is thus mainly concerned with influencing the shock pattern. As is readily noted by simple calculations, this situation no longer prevails in narrow flow channels. Here frictional and shock pressure losses are of the same order. In practical situations it is immaterial whether the flow is slowed down by a single normal shock at the Mach number of the nozzle exit, or whether friction in a narrow duct reduces the flow speed to a lower Mach number, at which in turn a weaker normal shock produces the transition to subsonic flow. Therefore the designer of an optimum "narrow" supersonic diffuser cannot be concerned with the shock pattern only. He must moreoever try to shorten the duct to minimize the high frictional losses.

The pressure recovery performance of supersonic diffusers depends on the chosen geometry. Surprisingly though, the geometry has only a limited influence on the diffuser length required to achieve this full pressure recovery. The recovery length of all diffuser types tested were similar to those found in the straight duct diffuser. Therefore, the earlier results reproduced from Merkli[10] in Fig. 28 are independent of diffuser geometry. This is in agreement with the data reported by Zerr[4,†], who claimed surprisingly short recovery lengths. It is remarkable to note that the recovery length is indeed a function of the initial parameters only independent of the diffuser geometry.

Another important result of this investigation is that at the low Reynolds numbers of our narrow flow channels, no great improvement in pressure recovery was found by the possible further closing of the second throat beyond the minimum starting area ratio, after the flow was established. Thus in our range of flow parameters, the simple fixed geometry diffusers perform practically as well as the more complicated adjustable ones.

We had difficulties in designing a good wedge diffuser in which oblique shock reduce the pressure more efficiently than the shock systems found in straight ducts. The reason for this is believed to be the poorly known shock interaction with the rather thick boundary

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† Since Zerr does not explicitly state the boundary layer parameter of his experiments, its value was estimated using Tucker's method[15]. It was shown previously (Merkli[10], Report #4, on preparation) that this is a reliable procedure.

layers found in narrow flow channels.

In this investigation the minimum diffuser throat area ratios (A**/A) have been found to be independent of the Reynolds number. This is consistent with time estimates for the duration of flow starting[†] and boundary layer development. The latter is much bigger than the starting time.

As noted in previous experiments, diffusers operating at optimum performance conditions are highly susceptible to small disturbances. Together with the hysteresis of flow starting and flow break down. This sensitivity will prevent optimum use of the diffuser to always insure stable operation.

In comparing our work with results from other diffuser investigations, we make the following suggestions: a) In most experiments reference is made to the diffuser performance in terms of pitot pressure. Difficulties arise with the method due to non-uniform pitot pressure distributions, suggesting that all comparisons ought to be based on static pressures. b) Often diffuser performance is defined as a percentage of normal shock recovery. Yet the normal shock recovery depends strongly on the Mach number, which in turn often is not known

[†] Results in preparation.

accurately. Therefore stating the measured increase in static pressure would be more reliable. Such problems do not arise comparing the diffusers described in this work, since always the same nozzle was used. Thus our diffusers all had the same initial conditions.

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Flexible wall diffuser, L/D = 15.

12 Maximum static pressure recivery (p_2/p_o) as a function of the location of the recovery zone.
L/D = 15, $5\times10^4 < Re_D < 3\times10^5$.

13 Pressure distribution in the flexible wall diffuser for various positions of the second throat.
p_o = 2286 Torr, L/D = 30.

14 Maximum pressure recovery (p_2/p_o, p_{t2}/p_o) for the flexible wall diffuser.
p_o = 400 Torr, L/D = 30.

15 Maximum pressure recovery (p_2/p_o, p_{t2}/p_o) for the flexible wall diffuser.
p_o = 765 Torr, L/D = 30.

16 Maximum pressure recovery (p_2/p_o, p_{t2}/p_o) for the flexible wall diffuser.
p_o = 2286 Torr, L/D = 30.

17 Pitot pressure surveys (p_{t2}/p_o) in the diffuser exit plane for increasing (1 to 5) diffuser back pressures (p_2/p_o).
p_o = 765 Torr, x**/D = 12, L/D = 15, h**/h = o.84.
In case 5 the proper nozzle flow is broken down.

18 Variation of the pitot pressure (p_{t2}/p_o) at various positions, y/h, in the diffuser exit plane for increasing back pressure (p_2/p_o).
p_o = 765 Torr, L/D = 15, h**/h = 1.0 (straight duct).

19 Static pressure distribution along the flexible wall diffuser.
p_o = 765 Torr, x**/D = 3, L/D = 15.

20 Static pressure distribution along the flexible wall diffuser.
p_o = 2286 Torr, L/D = 15.

21 Static pressure distributions along the flexible wall diffuser for various back pressures, p_2/p_o.
p_o = 765 Torr, x**/D = 9, L/D = 15, h**/h = 0.84.

22 Static pressure distribution along the flexible wall diffuser for various back pressures, p_2/p_o.
p_o = 765 Torr, x**/D = 12, L/D = 15, h**/h = 0.78.

23 Static pressure distribution in the wedge diffuser.
p_o = 765 Torr, x**/D = 12, L/D = 15.

24 Static pressure distribution in the wedge diffuser.
p_o = 400 Torr, x**/D = 4.2, L/D = 15, h**/h = 0.71.
1: with suction 2: without suction

25 Minimum second throat height ratios, $h^{**}/h = A^{**}/A$, for the wedge diffuser. $x^{**}/D = 4.2$, $L/D = 15$.

— —◈— — without suction

——— ⊙ ——— with suction

26 Maximum static pressure recovery (p_2/p_o) in the wedge diffuser.

◈ without suction

⊙ with suction

$x^{**}/D = 4.2$, $L/D = 15$, $h^{**}/h = 0.71$.

27 The effect of the second throat height ratio ($h^{**}/h = A^{**}/A$) on the maximum possible static pressure recovery, p_2/p_o, in the wedge diffuser, $x^{**}/D = 4.2$, $L/D = 15$.

Symbol					
	without suction	⊙	⊡	▽	/
	with suction	⊙	◈	△	⊙
p_o (Torr)		200	400	765	2281

28 The recovery length, $\Delta x/D$, as a function of the Mach number, M, and the boundary layer parameter, δ^*/D, taken from staright duct experiments (Merkli[10]).

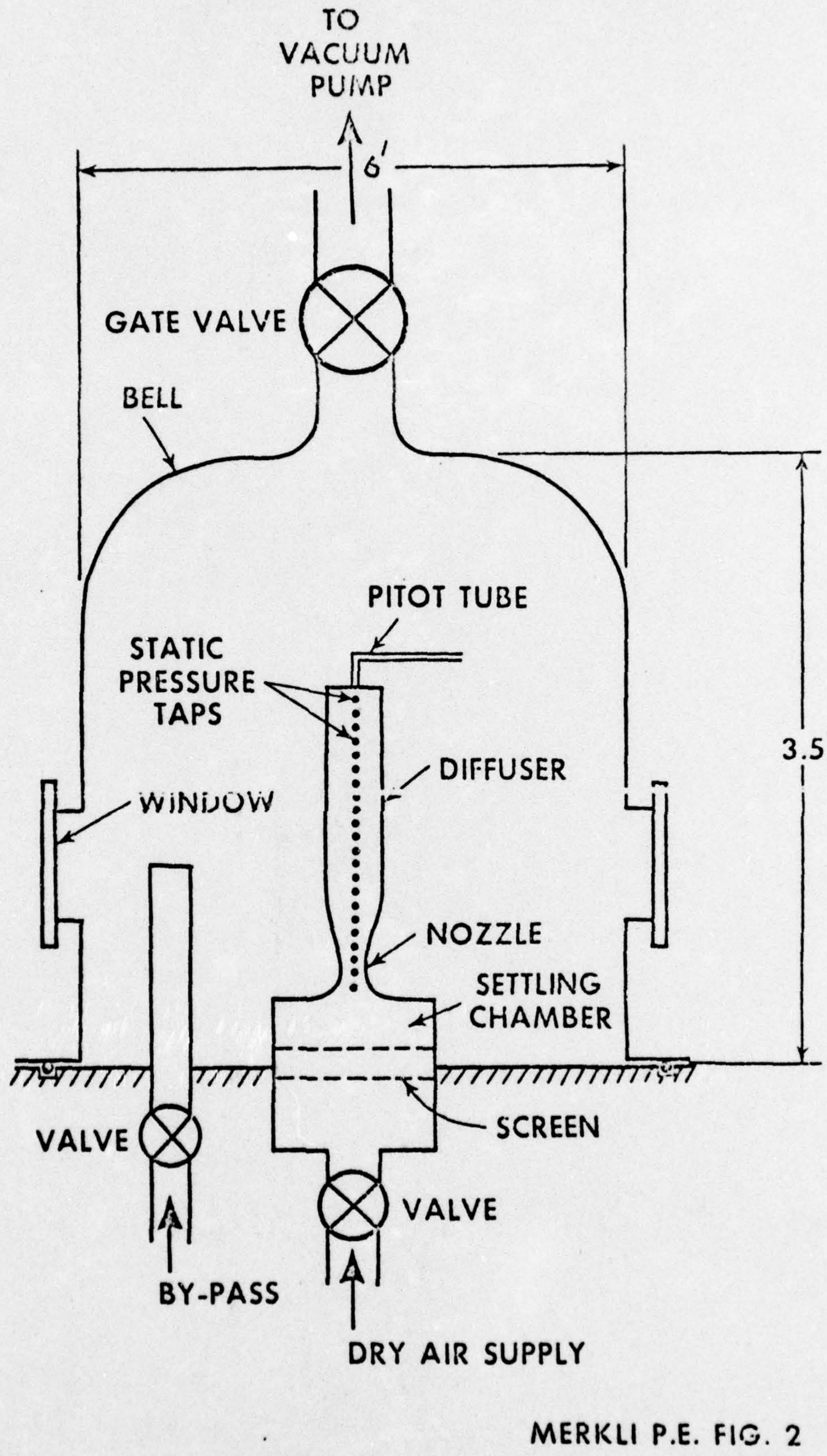

TO
VACUUM
PUMP
6'
GATE VALVE
BELL
3.5'
PITOT TUBE
STATIC
PRESSURE
TAPS
DIFFUSER
WINDOW
NOZZLE
SETTLING
CHAMBER
SCREEN
VALVE
VALVE
BY-PASS
DRY AIR SUPPLY
MERKLI P.E. FIG. 2

Figure 1.

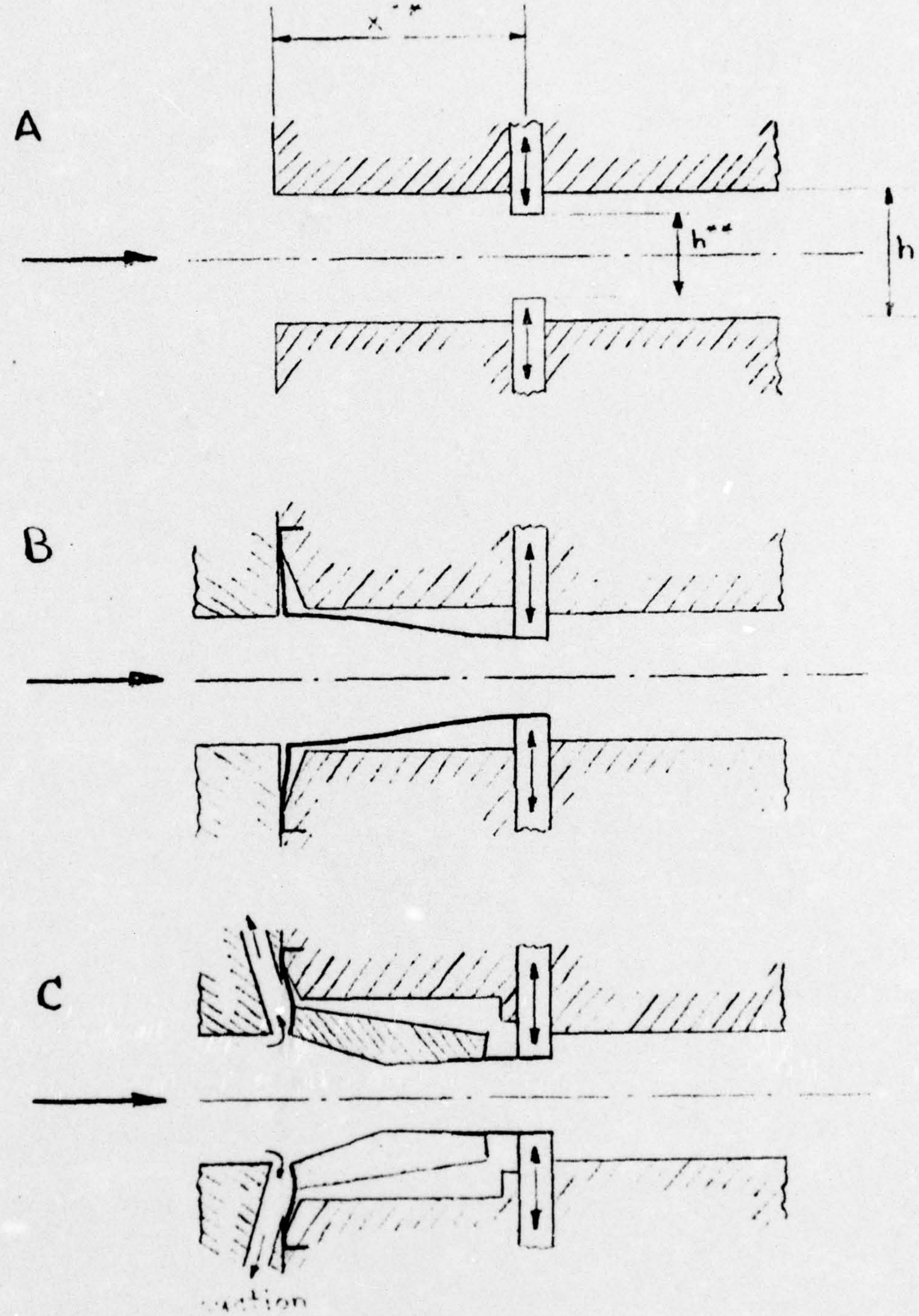


Figure 2.

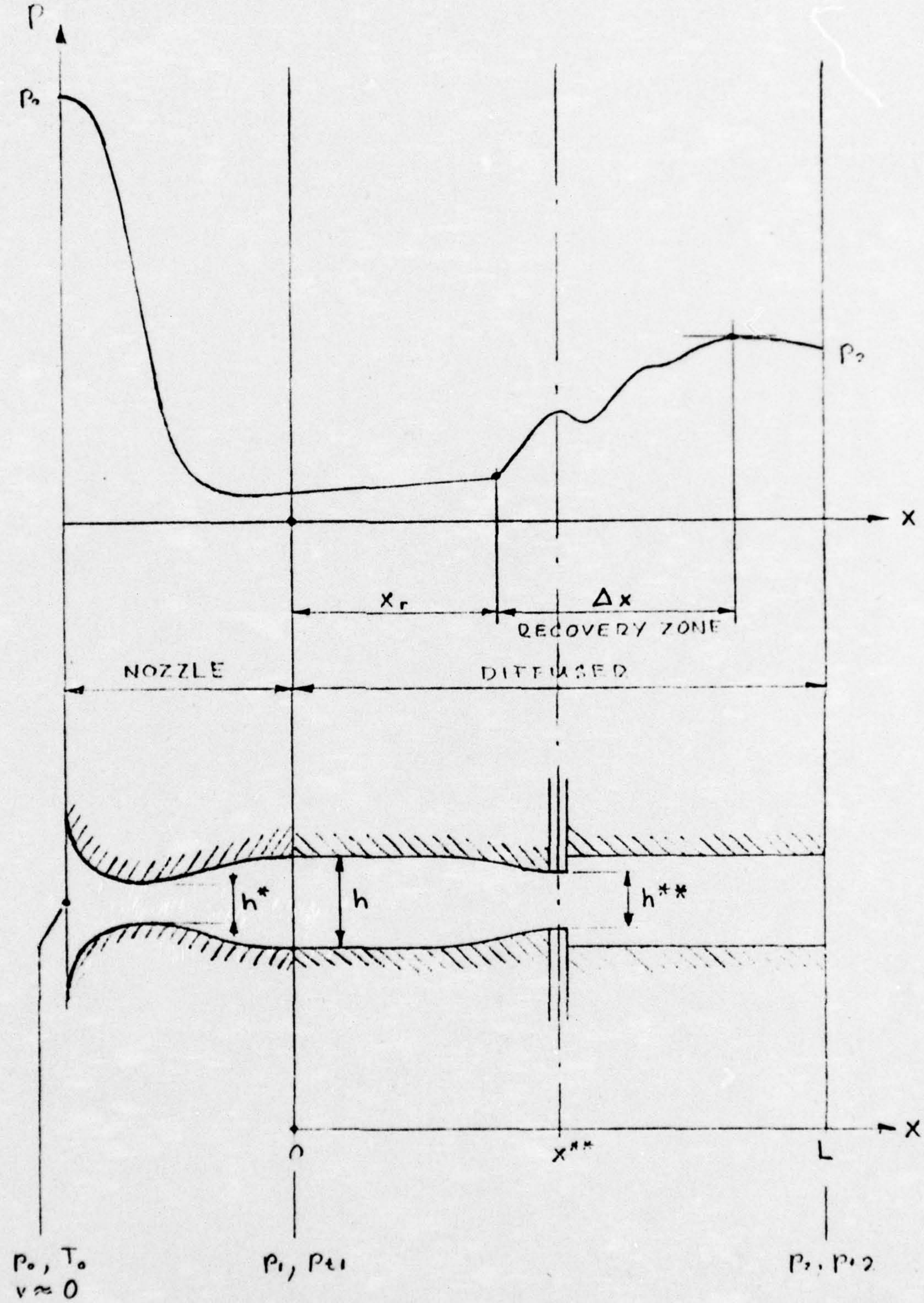
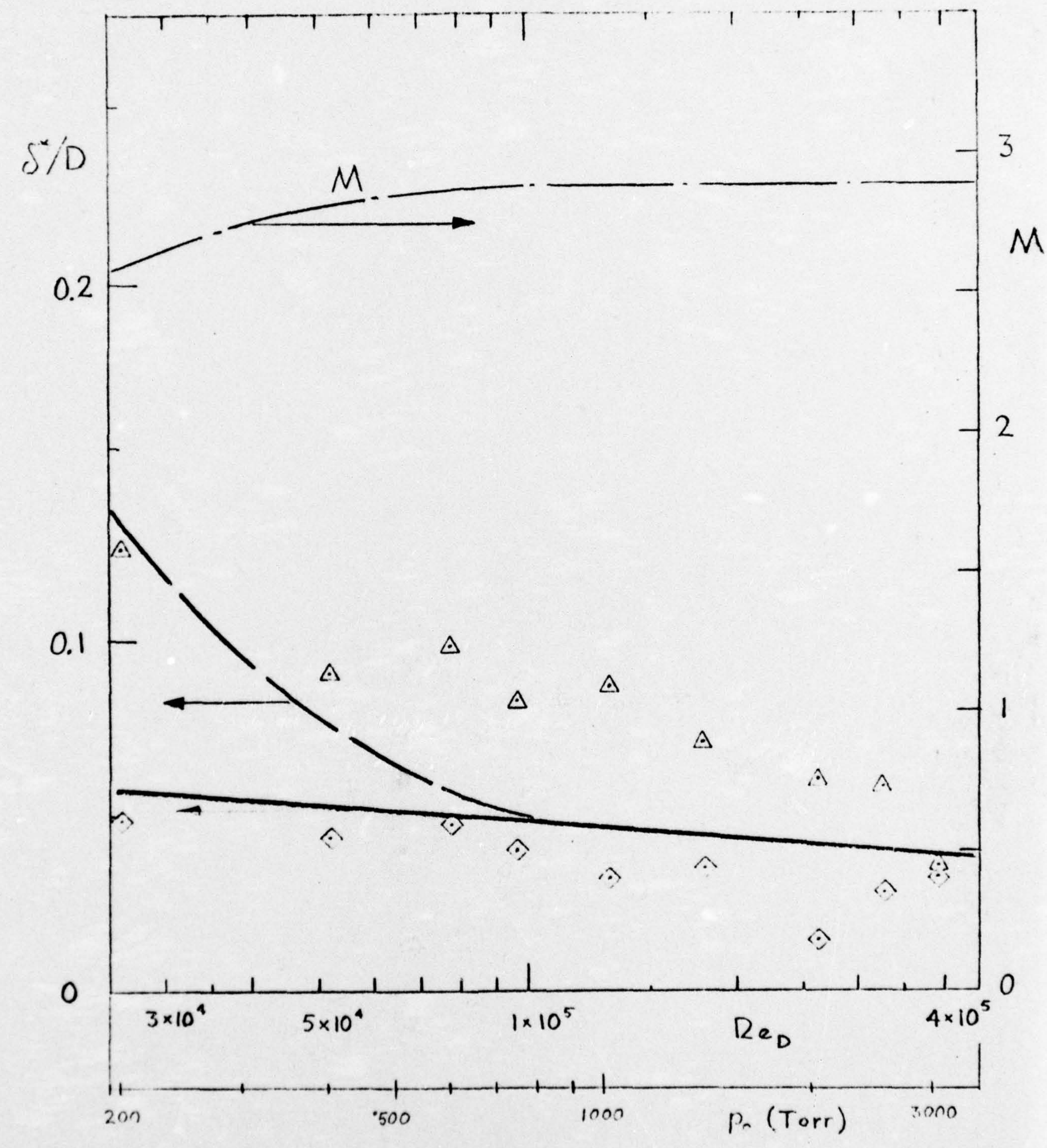

P
X
X_r
Δx
RECOVERY ZONE
NOZZLE
DIFFUSER
h^*
h
h^{**}
X
0
X^{**}
L
P_0, T_0
$v \approx 0$
P_1, P_{t1}
P_2, P_{t2}

Figure 3.



δ*/D
M
M
0.2
0.1
0
3
2
1
0
3×10⁴
5×10⁴
1×10⁵
4×10⁵
Re_D
200
500
1000
3000
p₀ (Torr)

Figure 4.

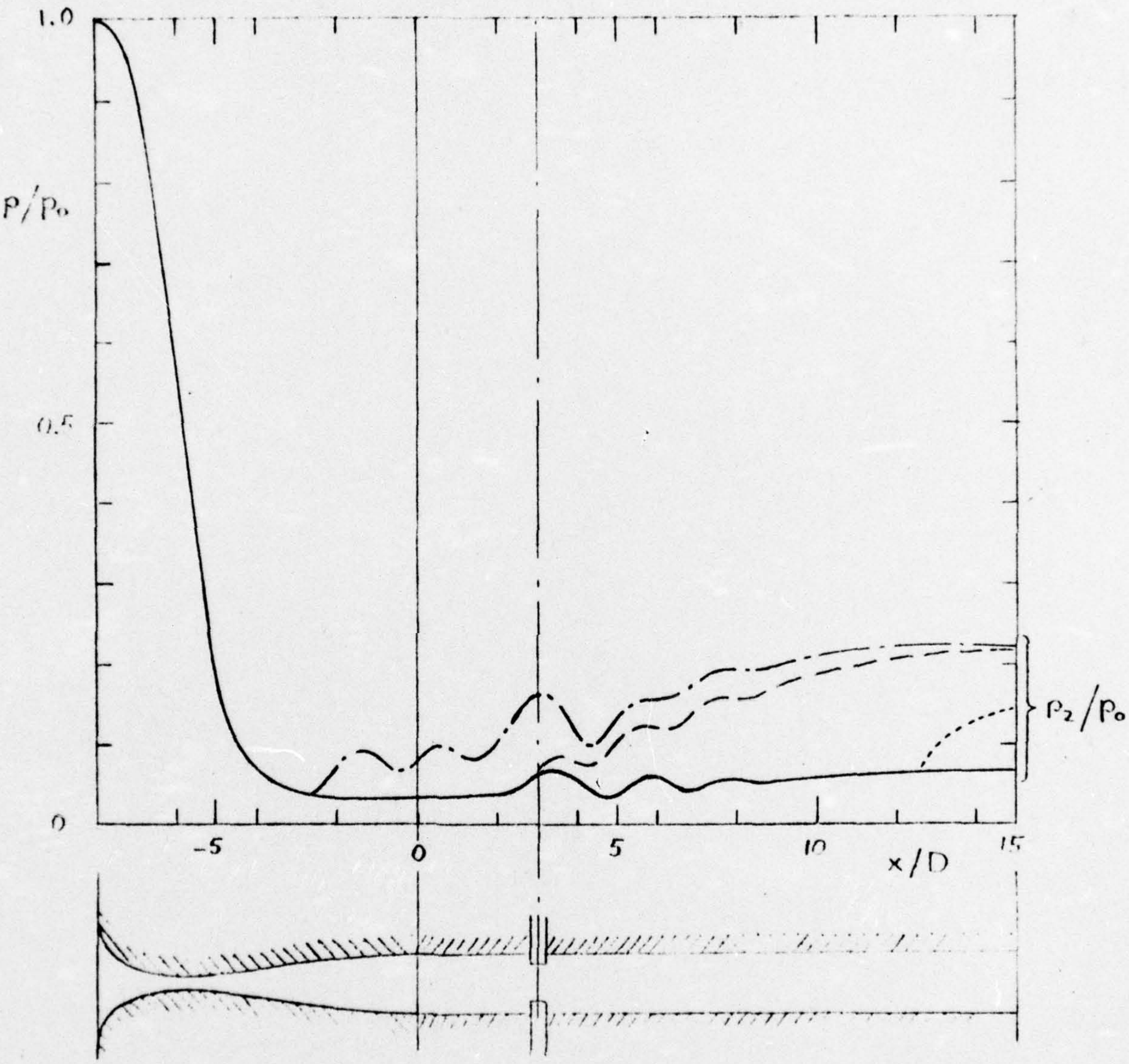


Figure 5.

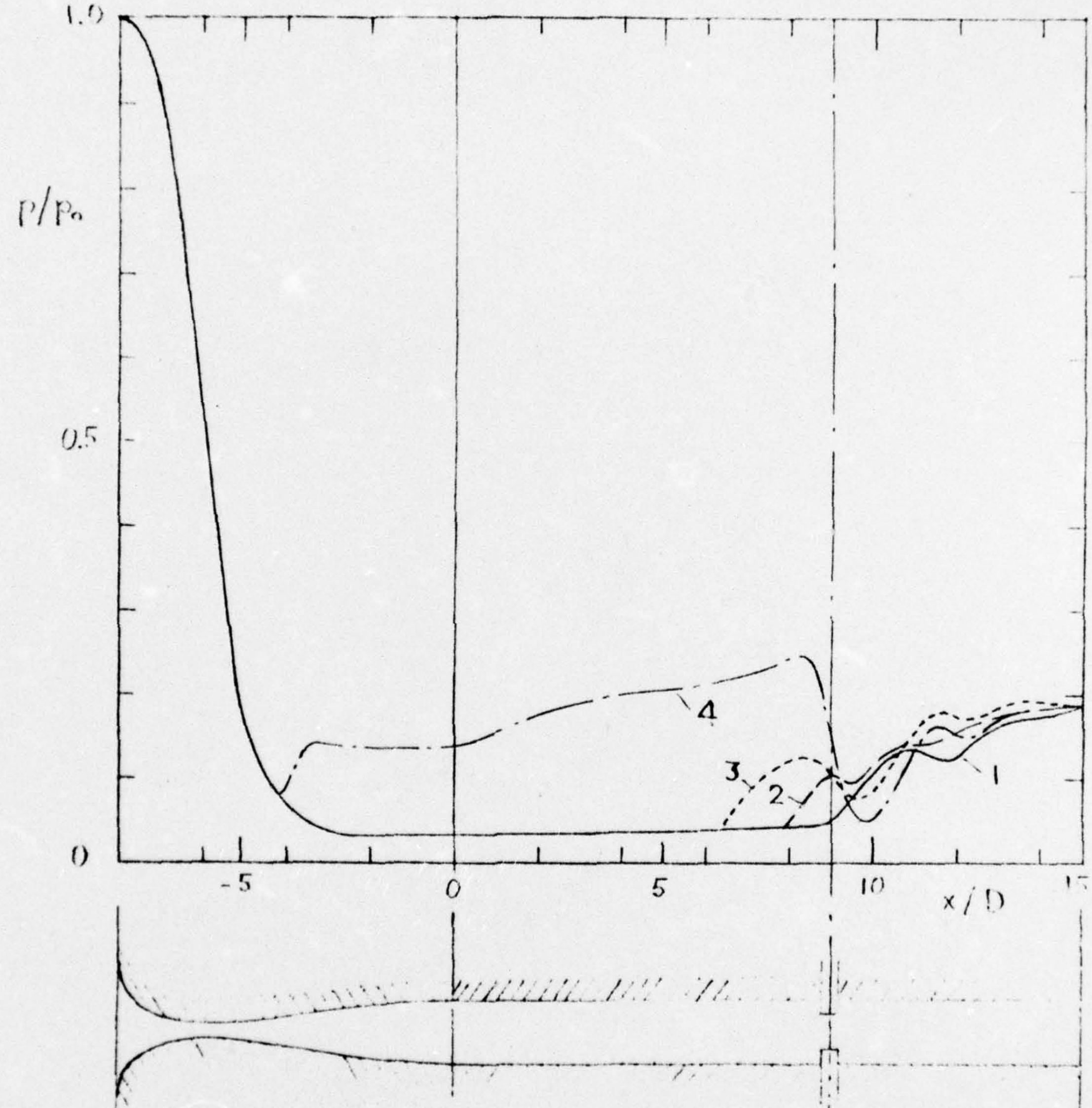
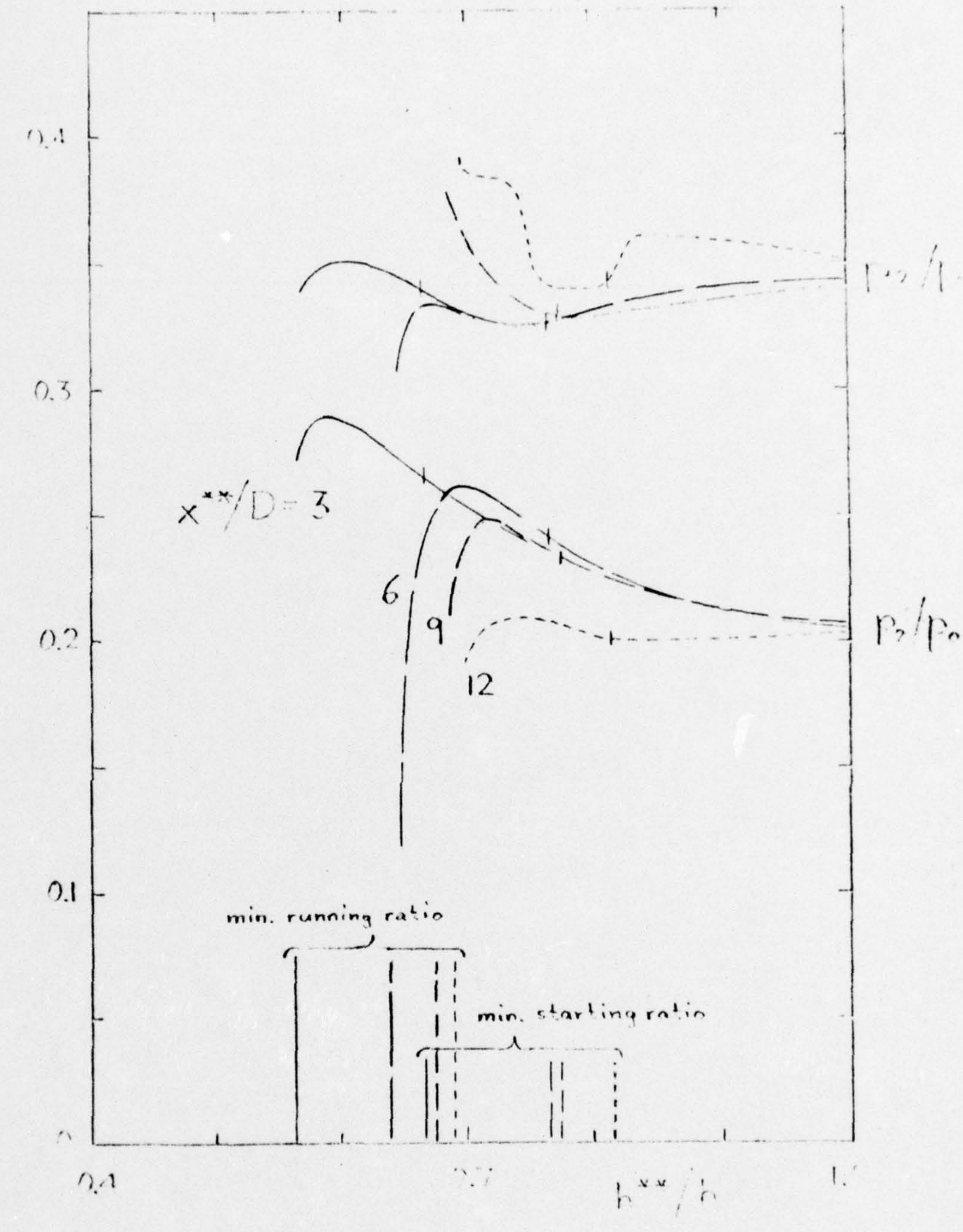


Figure 6.



0.4
0.3
0.2
0.1
0
0.4
0.7
1.0
$x^{**}/D=3$
6
9
12
p_2/p_0
min. running ratio
min. starting ratio
h^{**}/h

Figure 7.

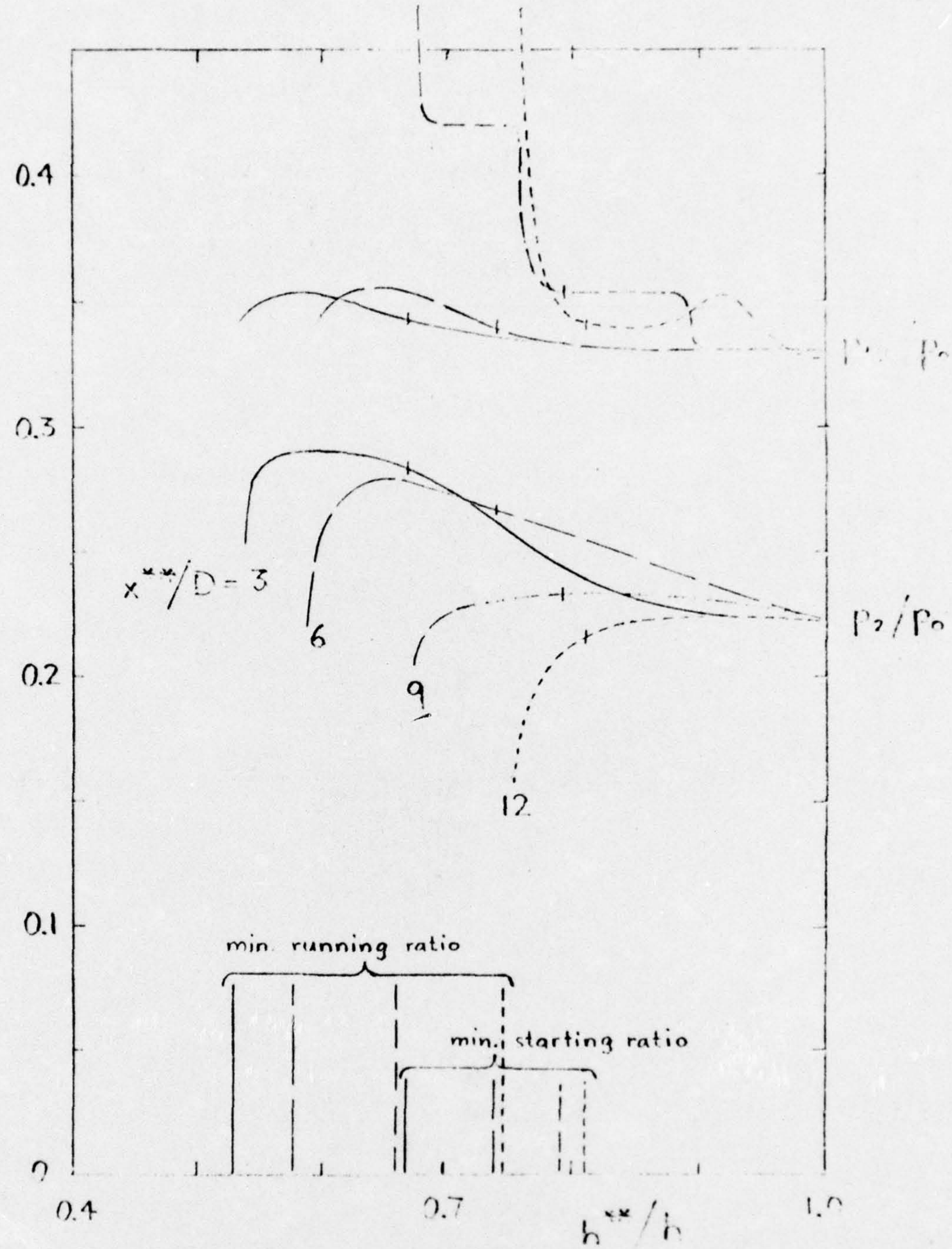
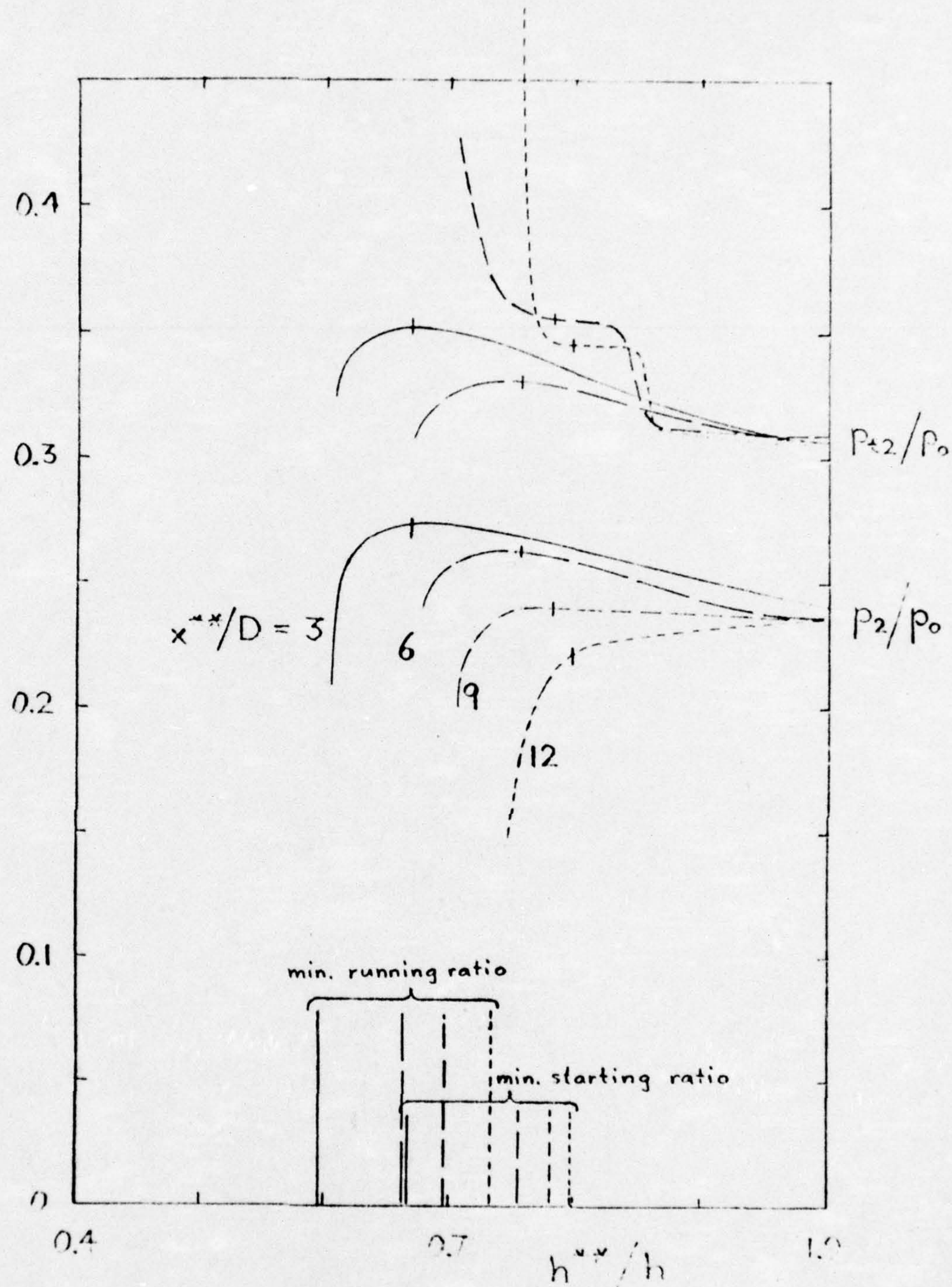

0.4
0.3
0.2
0.1
0
0.4
0.7
1.0
h^{**}/h
$x^{**}/D = 3$
6
9
12
p_2/p_0
min. running ratio
min. starting ratio

Figure 8.



0.4
0.3
0.2
0.1
0
0.4
0.7
1.0
p_{t2}/p_0
p_2/p_0
$x^{**}/D = 3$
6
9
12
min. running ratio
min. starting ratio
h^{**}/h

Figure 9.

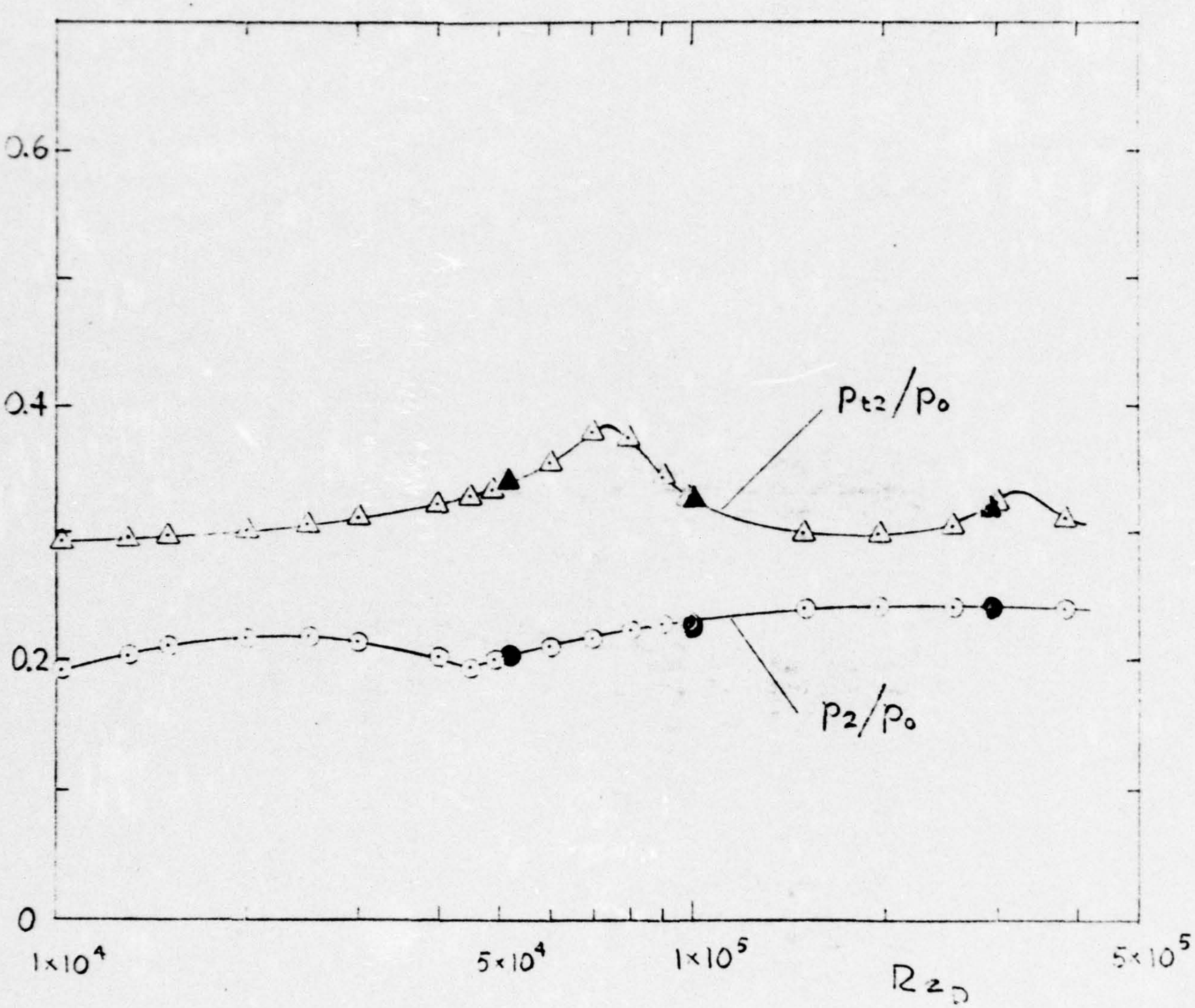


Figure 10.

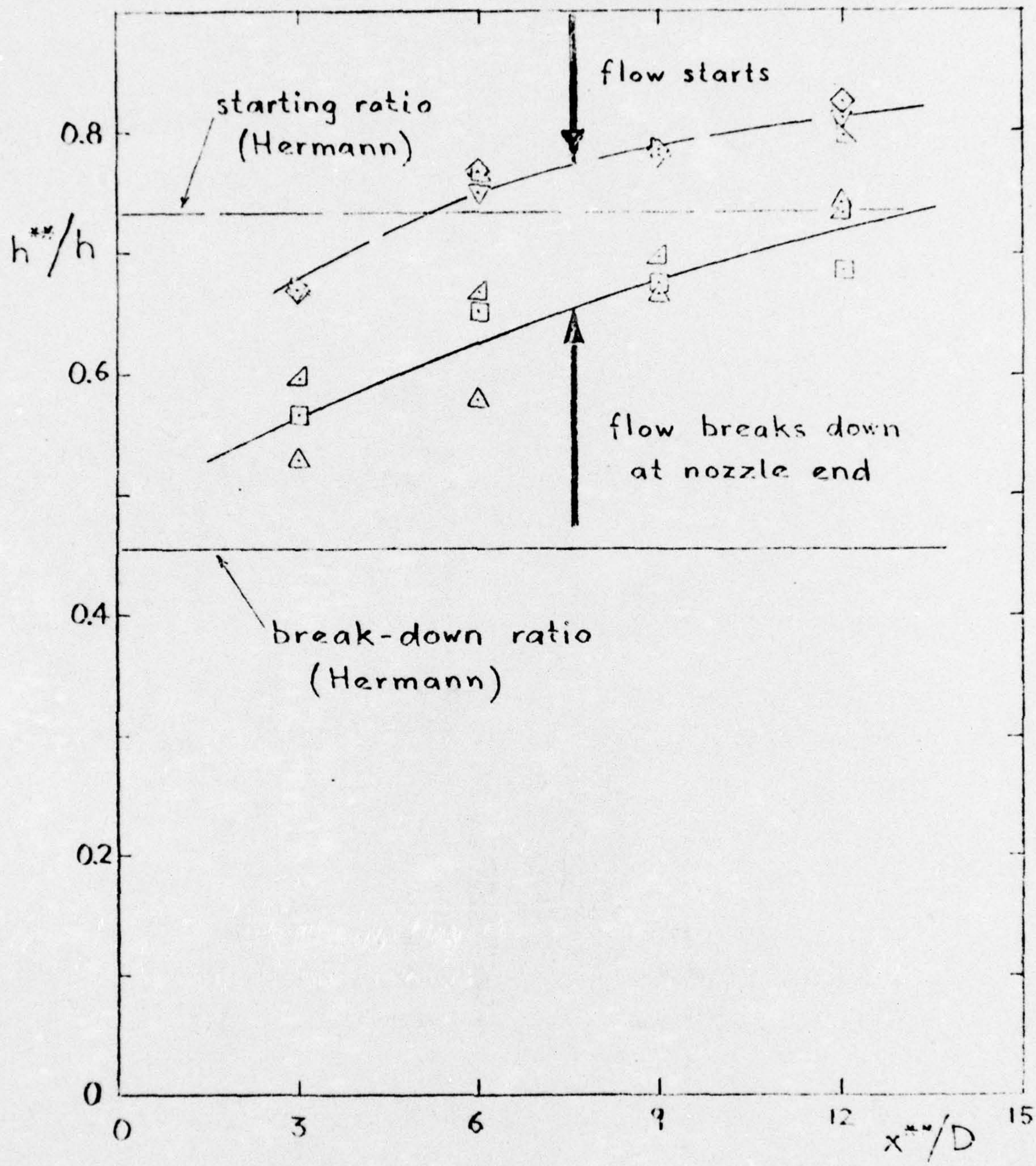
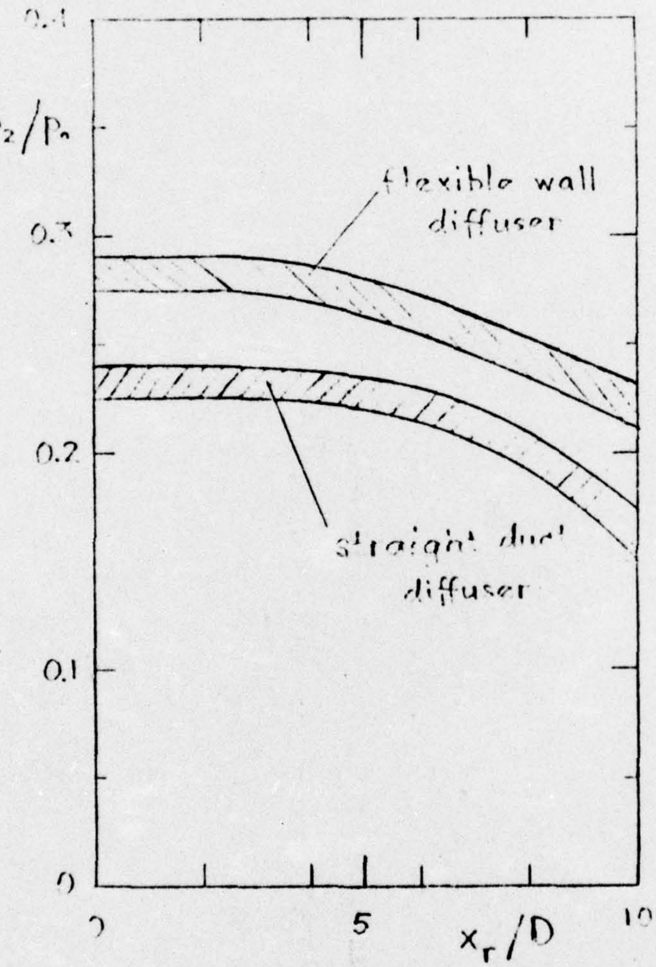

flow starts
starting ratio
(Hermann)
0.8
h**/h
0.6
flow breaks down
at nozzle end
0.4
break-down ratio
(Hermann)
0.2
0
0
3
6
9
12
15
x**/D

Figure 11



0.4
p_2/p_0
0.3
0.2
0.1
0
flexible wall diffuser
straight duct diffuser
0
5
10
x_r/D

Figure 12

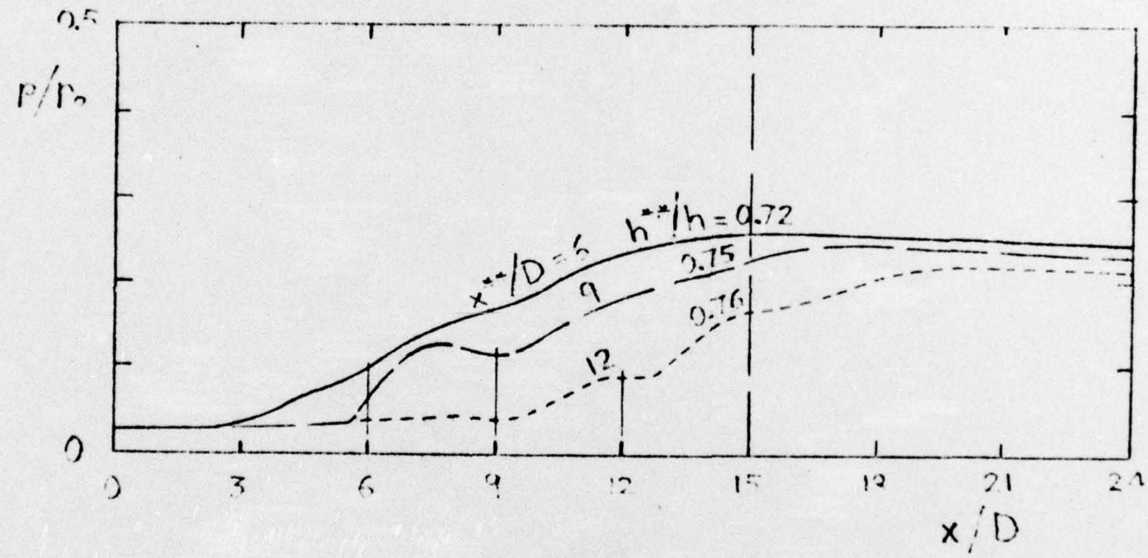
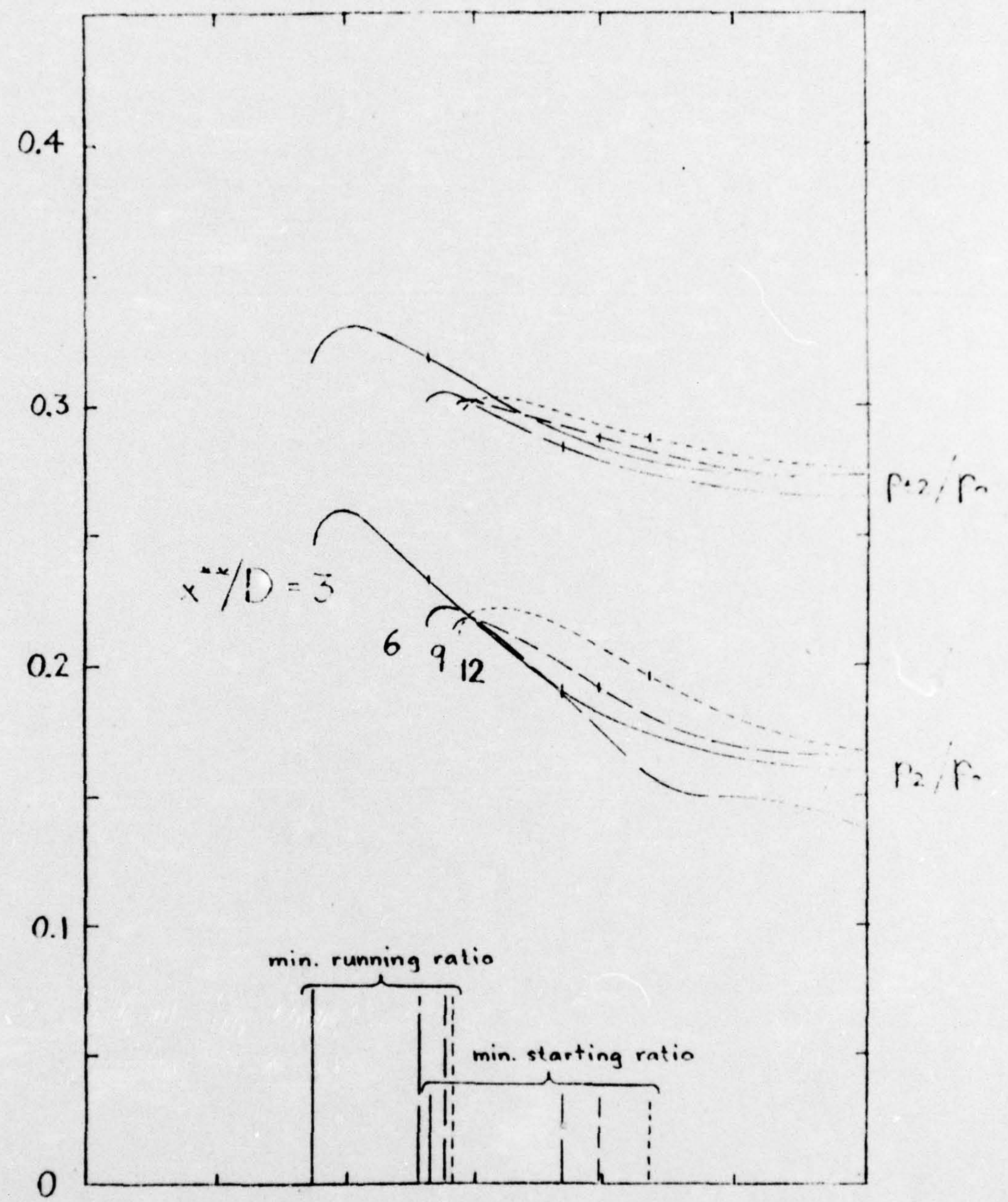
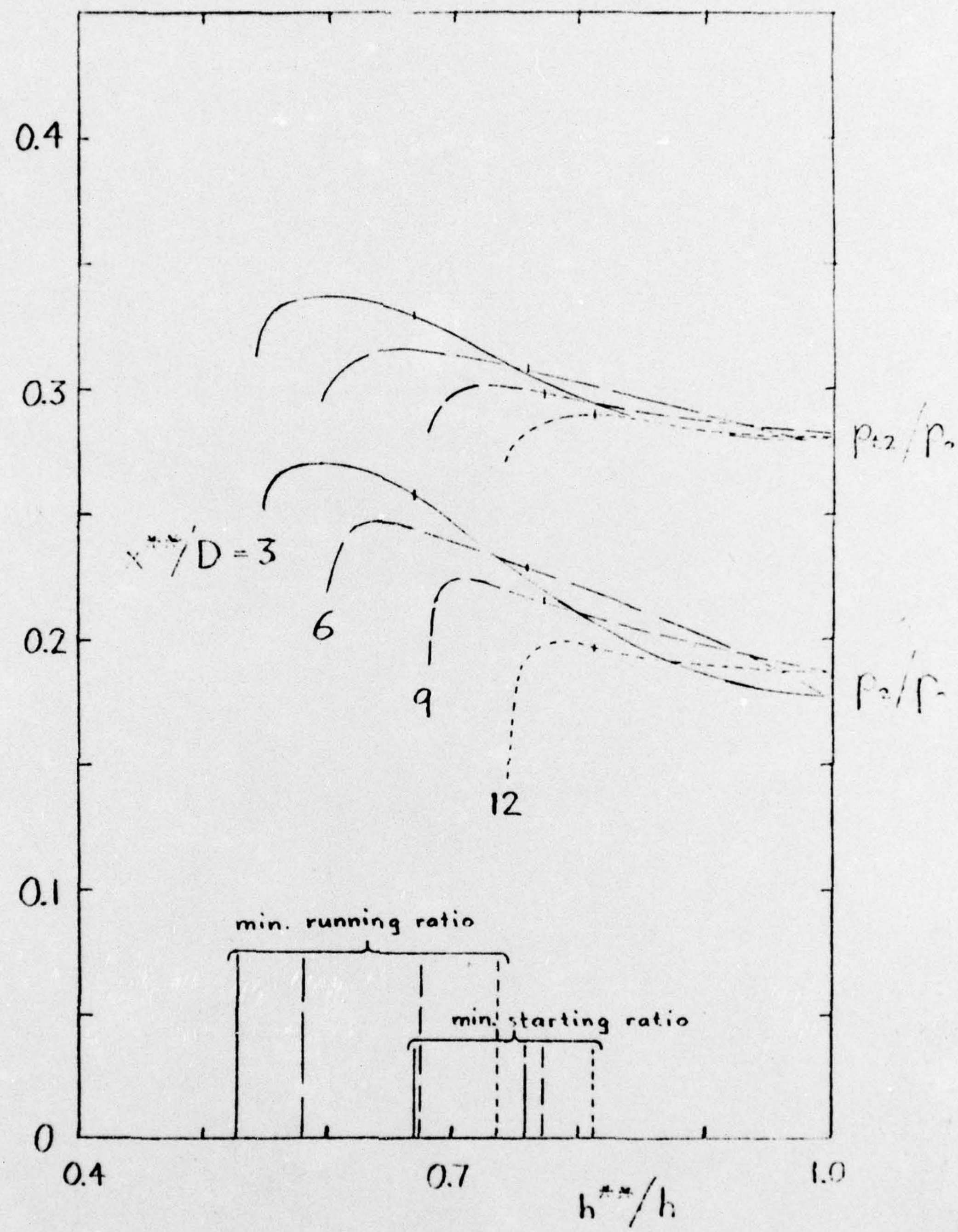


Figure 13



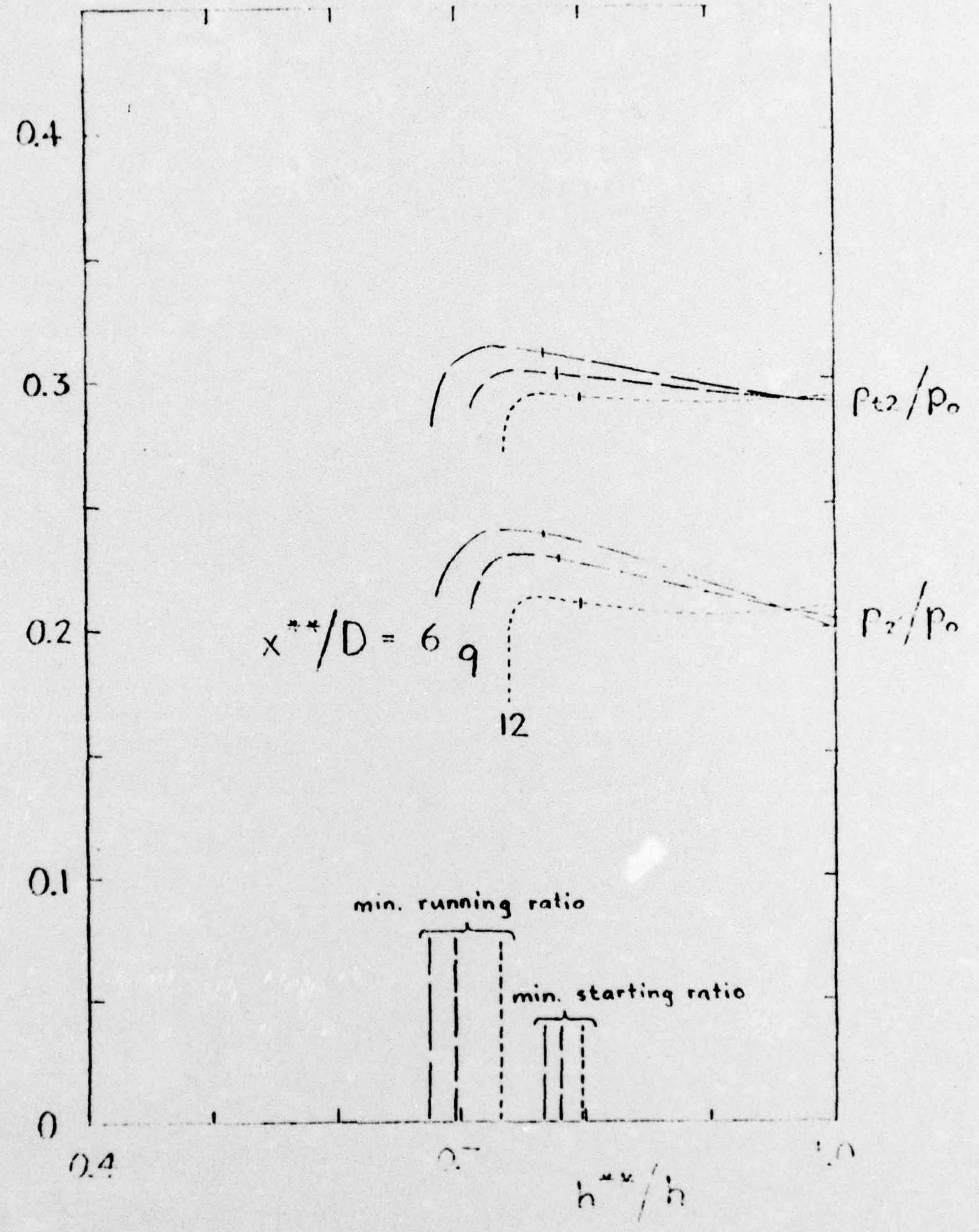
0.4
0.3
0.2
0.1
0
$x^{**}/D = 3$
6
9
12
min. running ratio
min. starting ratio
0.4
0.7
1.0
h^{**}/h

Figure 14



0.4
0.3
0.2
0.1
0
p_{t2}/p_0
$x^{**}/D = 3$
6
9
12
p_2/p_0
min. running ratio
min. starting ratio
0.4
0.7
1.0
h^{**}/h

Figure 15



0.4
0.3
0.2
0.1
0
p_{t2}/p_0
p_2/p_0
x^{**}/D = 6
9
12
min. running ratio
min. starting ratio
0.4
h^{**}/h

Figure 16

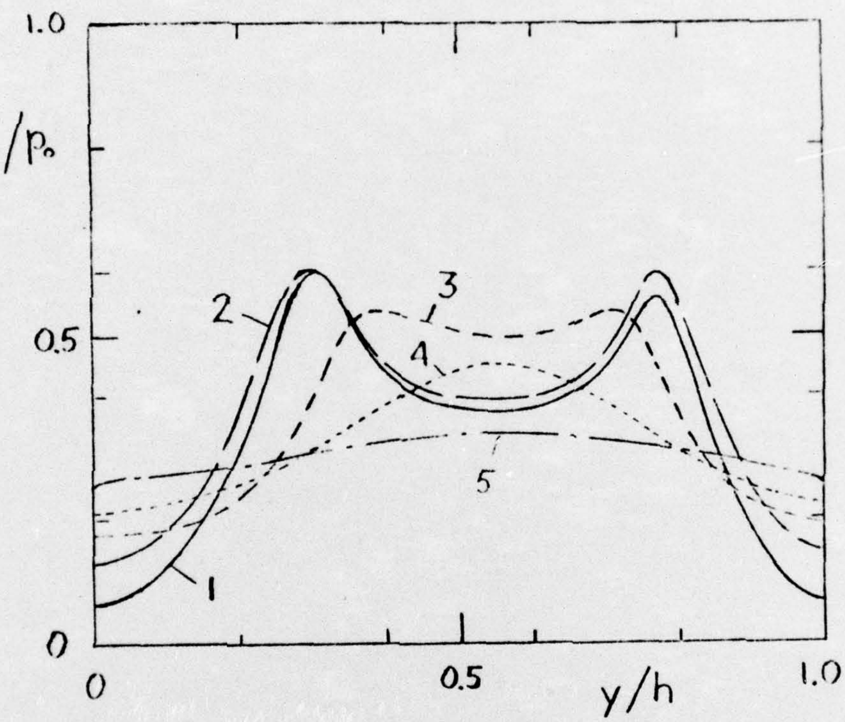
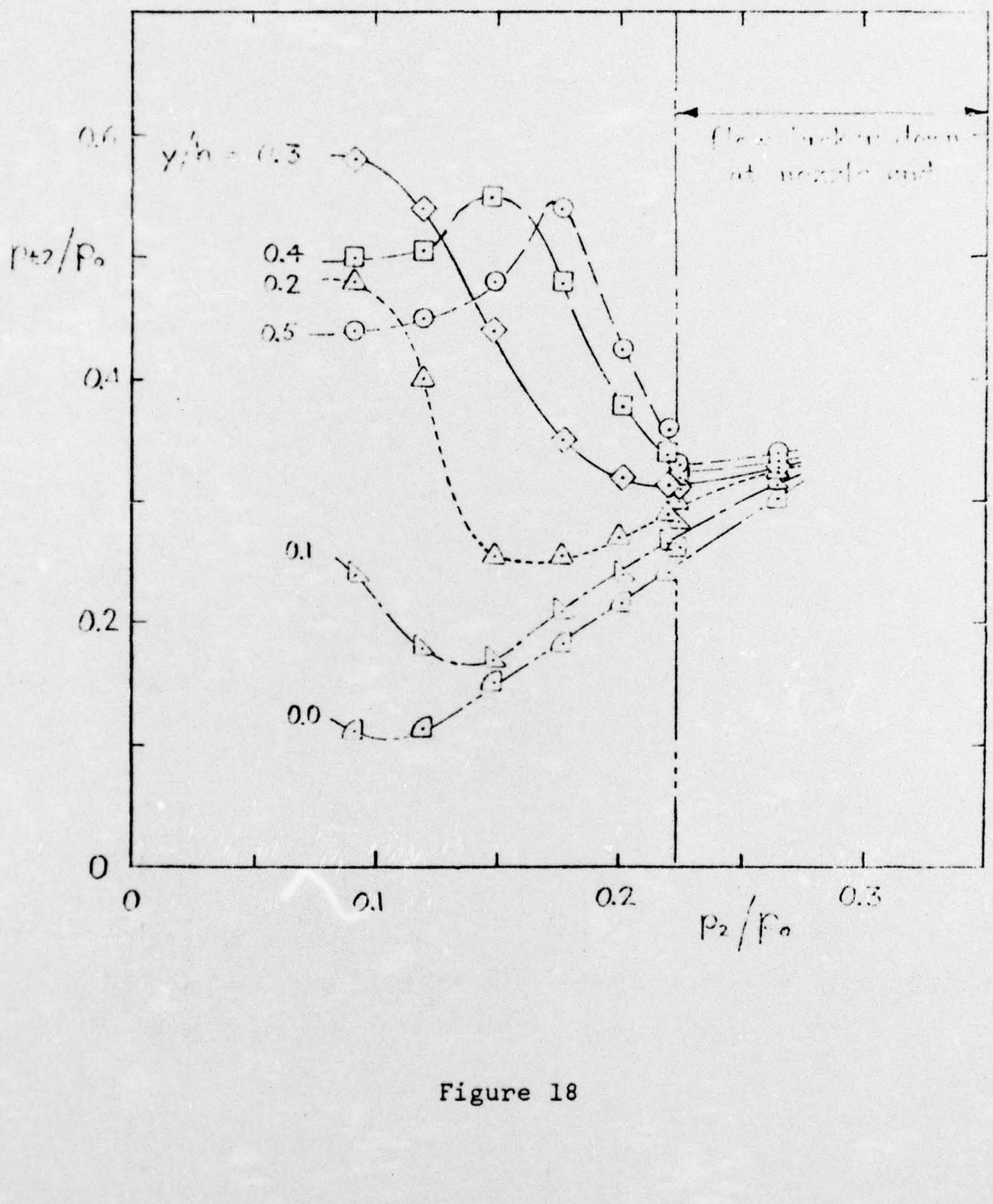


Figure 17



0.6
0.4
0.2
0
0
0.1
0.2
0.3
p_{t2}/p_o
p_2/p_o
y/h = 0.3
0.4
0.2
0.5
0.1
0.0
flow broken down
at nozzle end

Figure 18

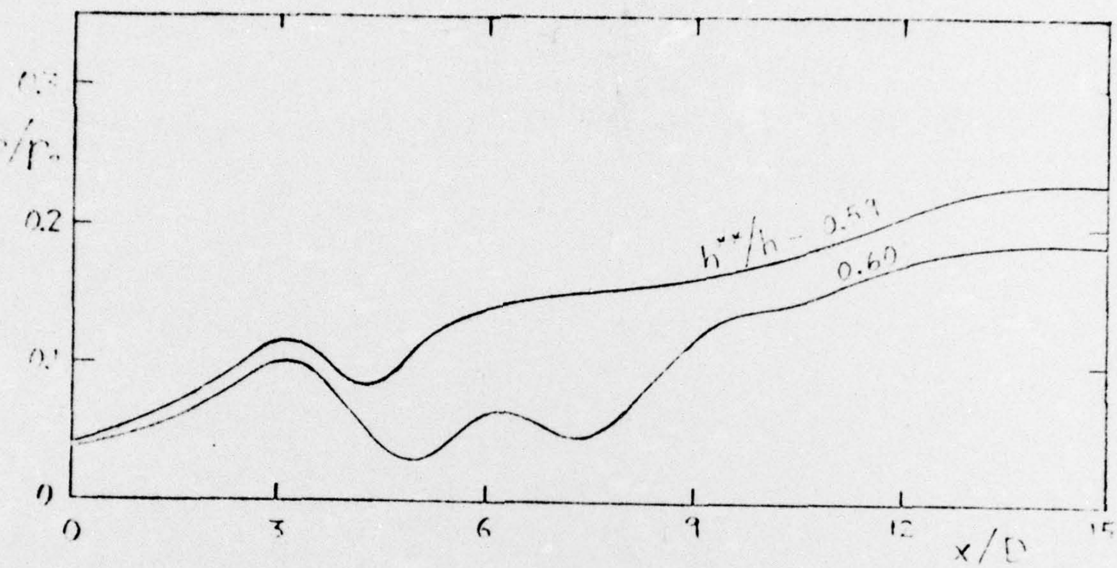


Figure 19

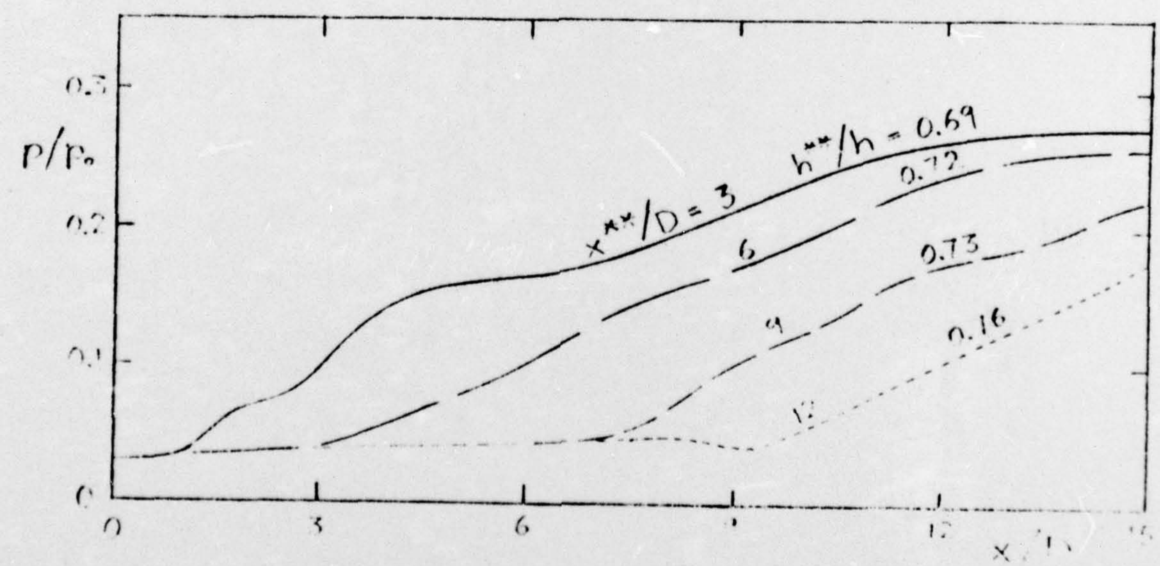


Figure 20

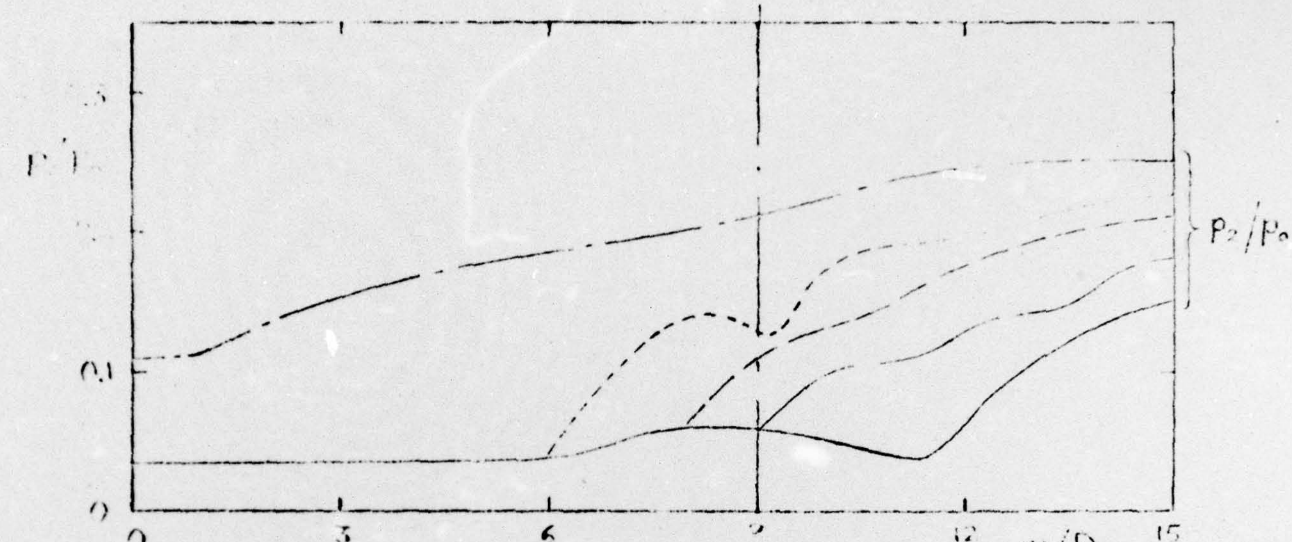


Figure 21

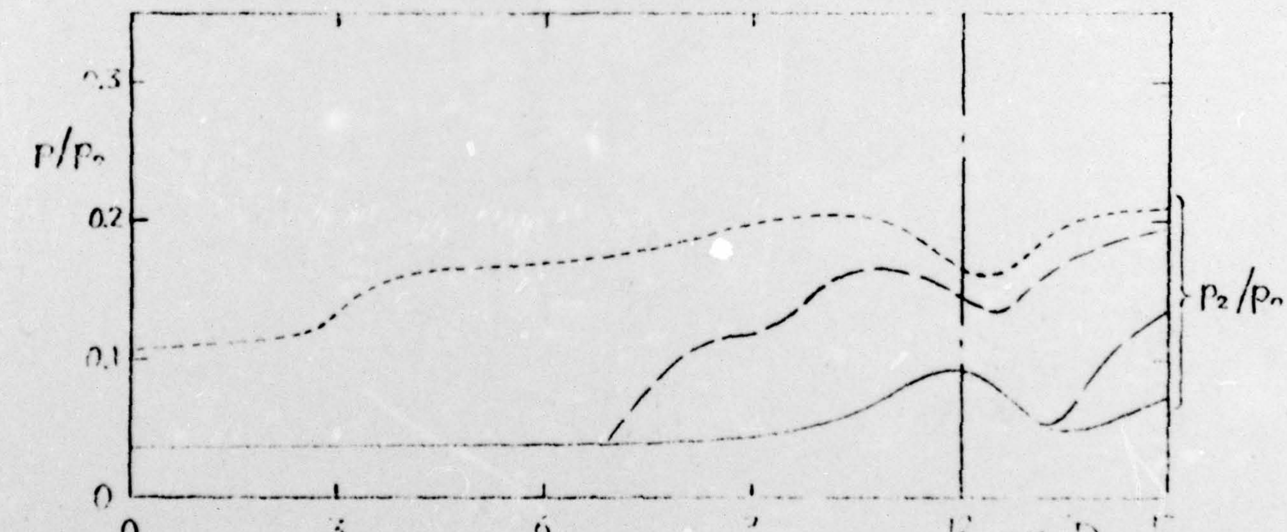


Figure 22

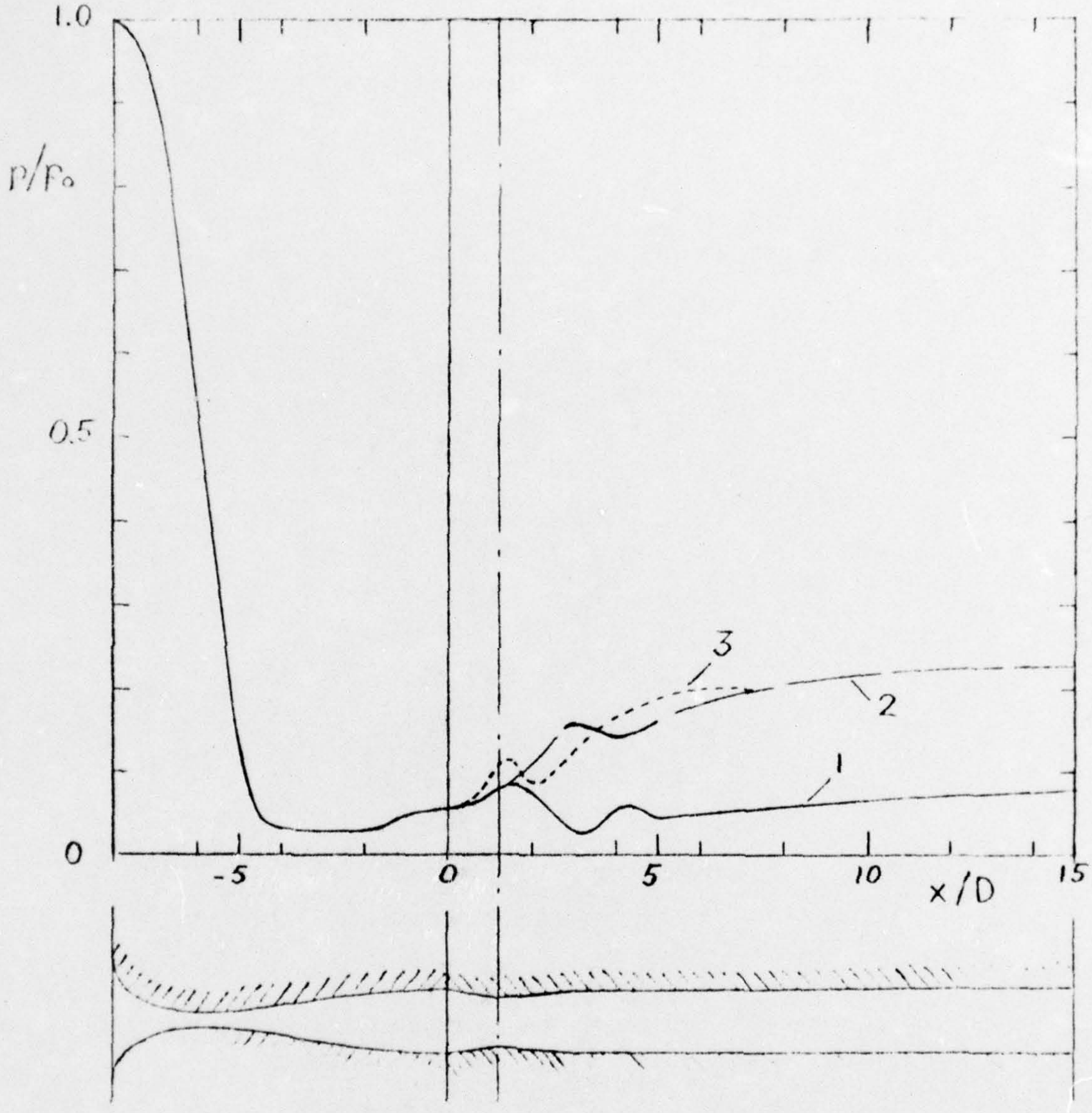


Figure 23

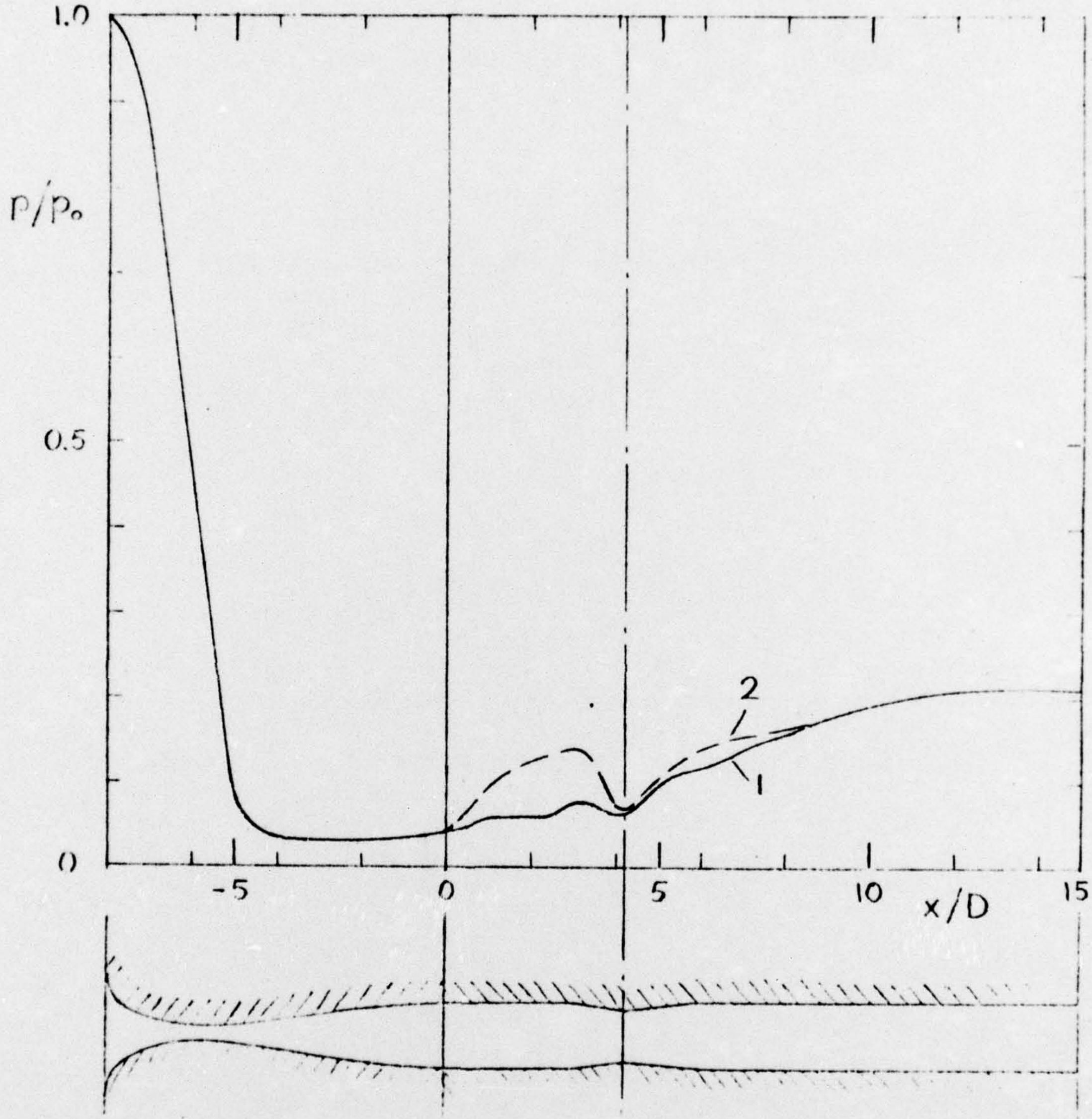


Figure 24

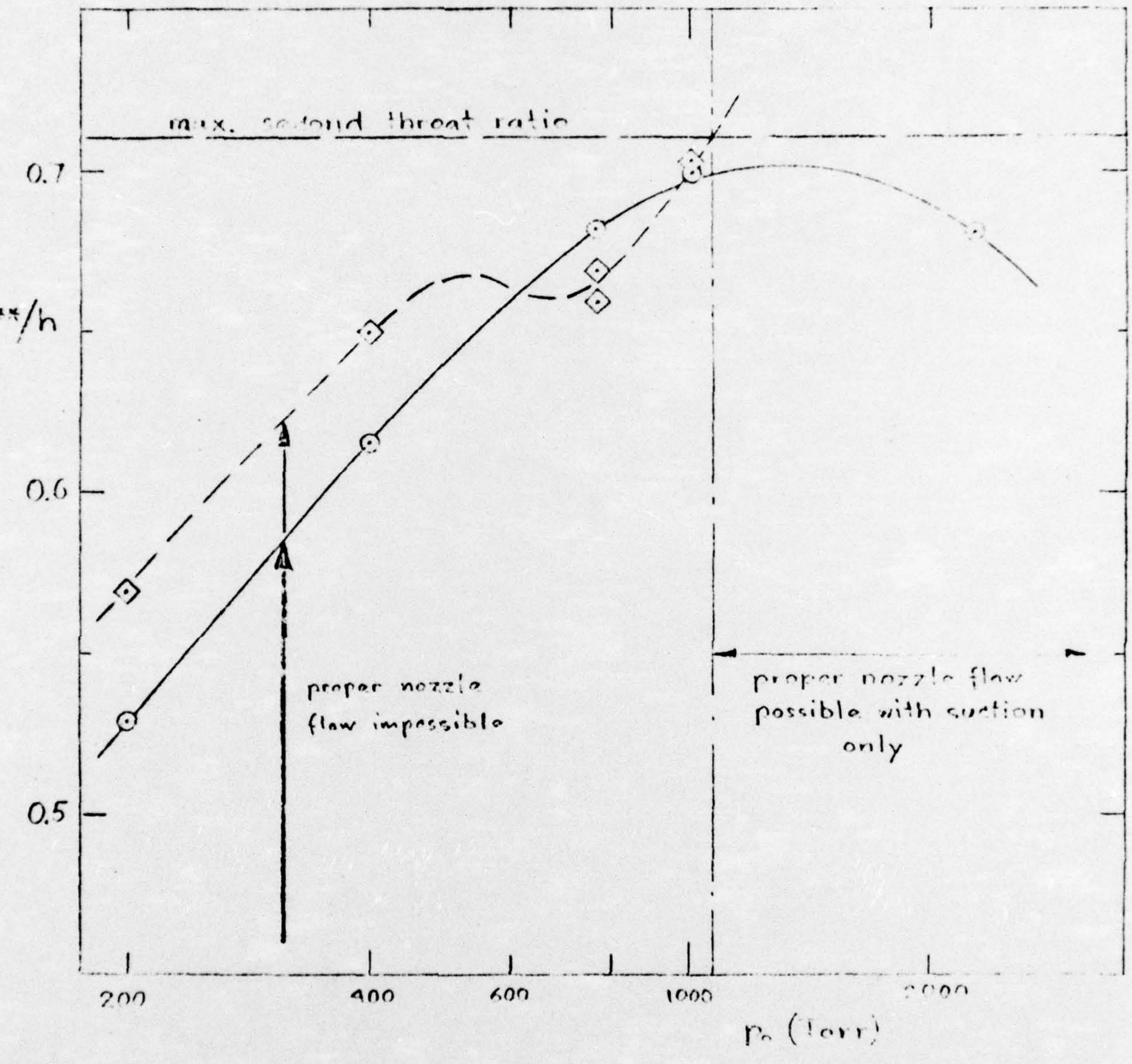
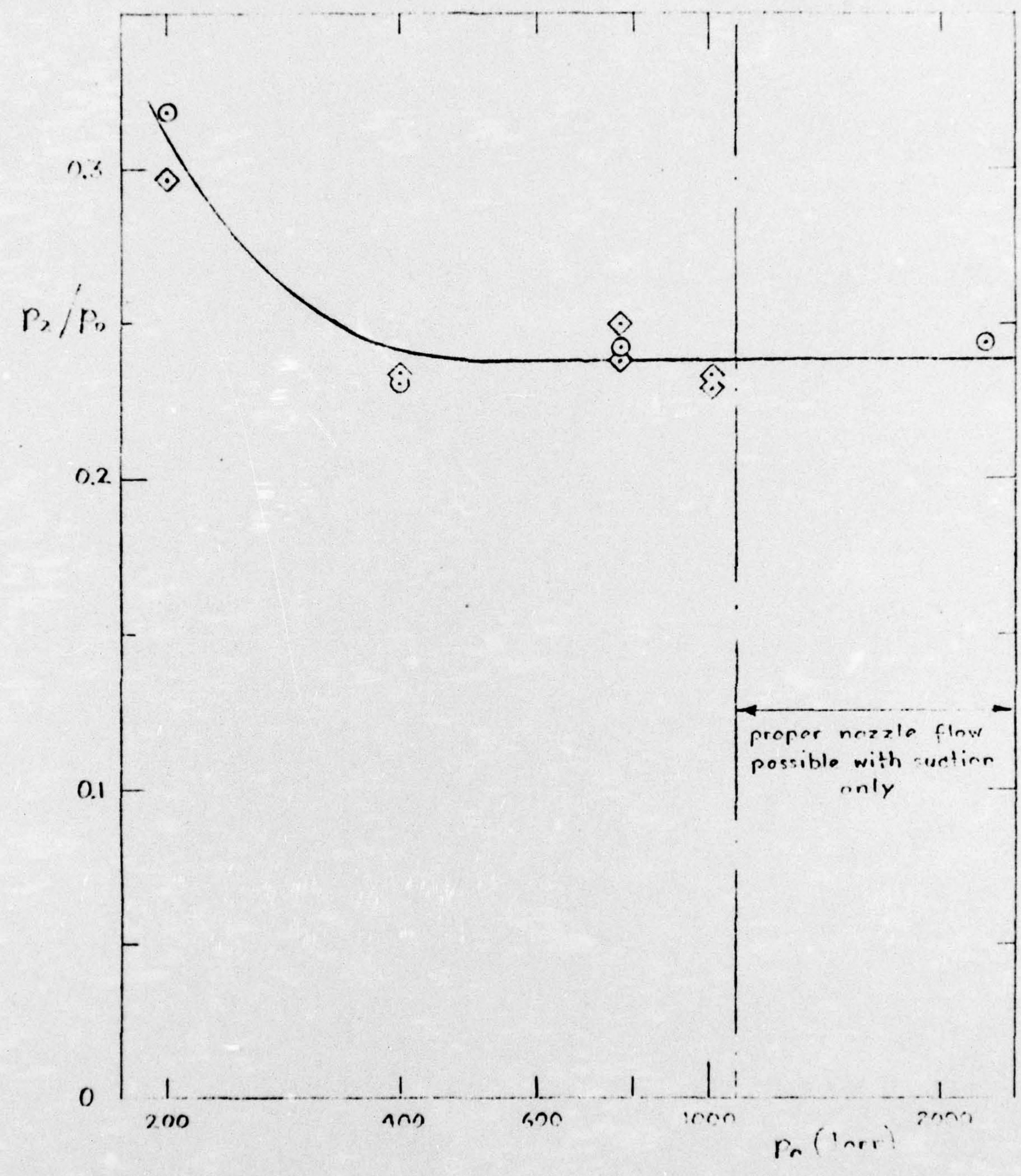
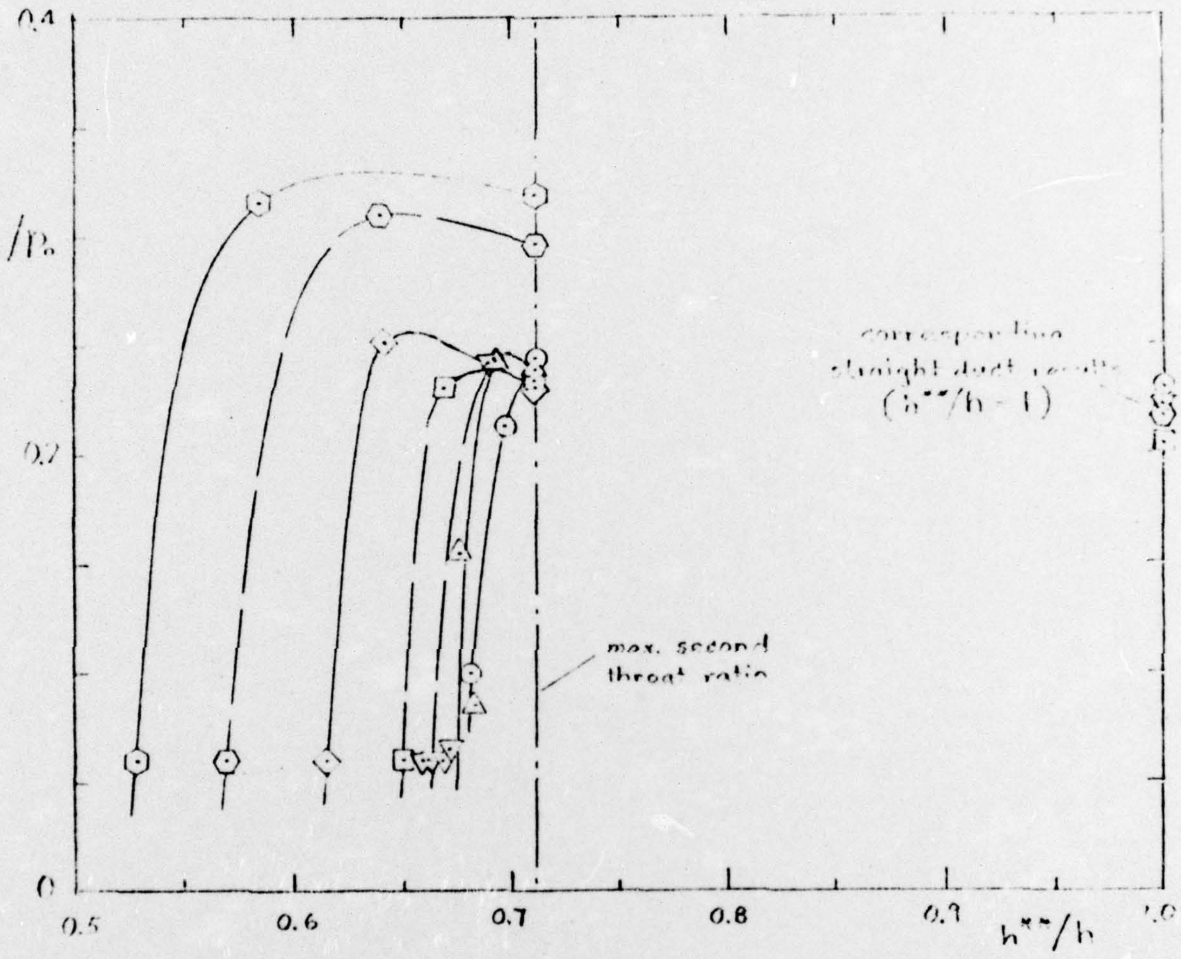

max. second throat ratio
0.7
0.6
0.5
h**/h
proper nozzle
flow impossible
proper nozzle flow
possible with suction
only
200
400
600
1000
2000
p₀ (Torr)

Figure 25



0.3
p_2/p_0
0.2
0.1
0
200
400
600
1000
2000
p_0 (Torr)
proper nozzle flow possible with suction only

Figure 26



0.4
P_2/P_0
0.2
0
0.5
0.6
0.7
0.8
0.9
1.0
h^{**}/h
corresponding straight duct results
($h^{**}/h = 1$)
max. second throat ratio

Figure 27

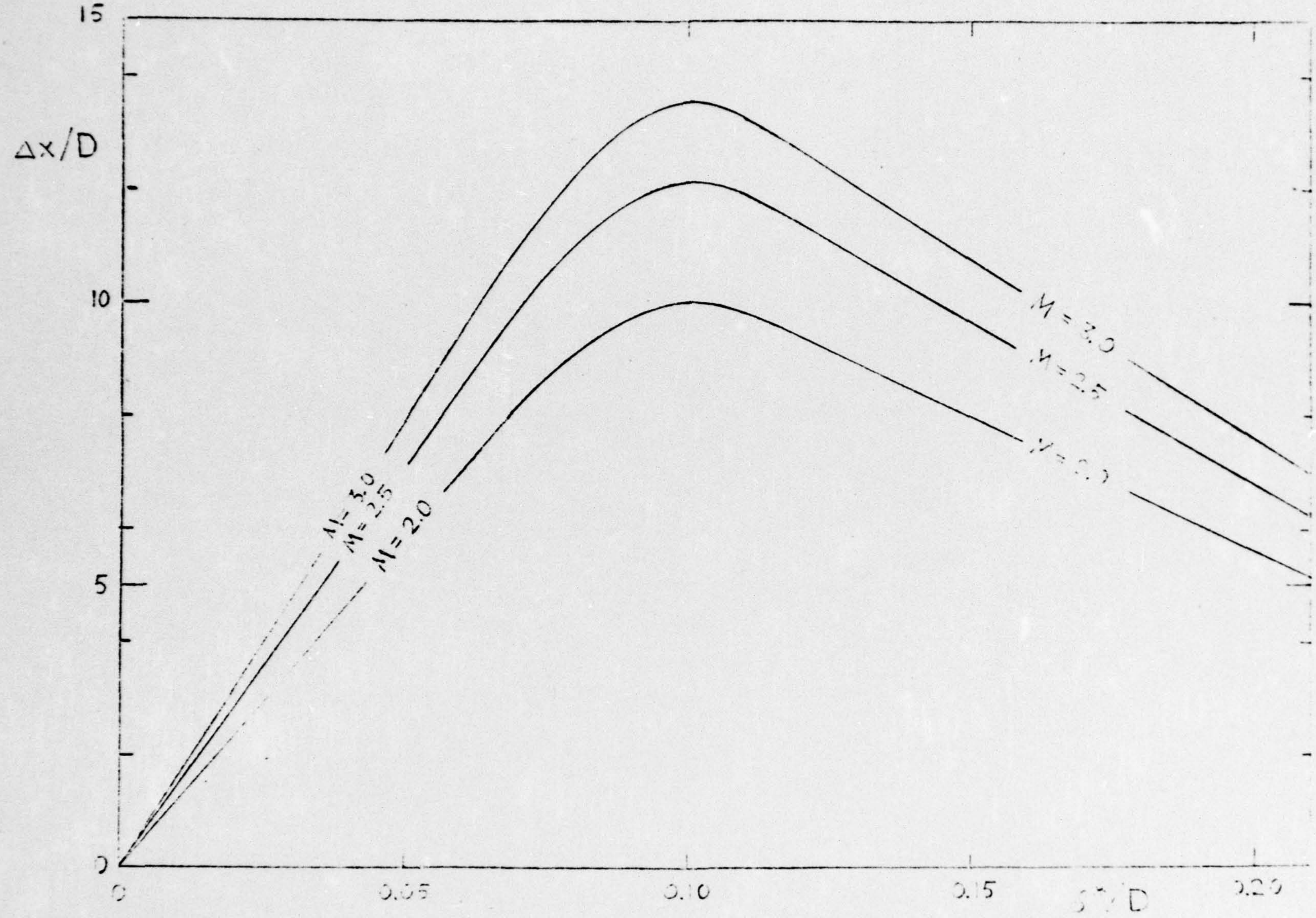


Figure 28